Renewable and Sustainable Energy Reviews 32 (2014) 810–853

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

An overview of fuel cell technology: Fundamentals and applications

Omar Z. Sharaf, Mehmet F. Orhan *

Department of Mechanical Engineering, College of Engineering, American University of Sharjah, PO Box: 26666, Sharjah, United Arab Emirates

ARTICLE INFO

Article history:
Received 3 September 2013
Received in revised form
27 December 2013
Accepted 4 January 2014
Available online 13 February 2014

Keywords:
Fuel cell
Hydrogen
Proton exchange membrane fuel cell (PEMFC)
Electrolyte
Cathode
Anode
Electrochemistry

ABSTRACT

This paper provides a comprehensive review of fuel cell science and engineering with a focus on hydrogen fuel cells. The paper provides a concise, up-to-date review of fuel cell fundamentals; history; competing technologies; types; advantages and challenges; portable, stationary, and transportation applications and markets; current status of research-and-development; future targets; design levels; thermodynamic and electrochemical principles; system evaluation factors; and prospects and outlook. The most current data from industry and academia have been used with the relation between fuel cell fundamentals and applications highlighted throughout the manuscript.

Contents

* Corresponding author. Tel.: +971 50 465 1959; fax: +971 6 515 2979.
E-mail addresses: omar.sharaf@alumni.aus.edu (O.Z. Sharaf), morhan@aus.edu (M.F. Orhan).

1364-0321/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2014.01.012

Abbreviations

AFC	alkaline fuel cell
APU	auxiliary power unit
BoP	balance of plant
CCHP	combined cooling, heating, and power
CHP	combined-heat-and-power
DMFC	direct methanol fuel cell
EPS	emergency back-up power supply
FCEB	fuel cell electric bus
FCEV	fuel cell electric vehicle
GDL	gas diffusion layer
GHG	greenhouse gas
H-FCEV	heavy-duty fuel cell electric vehicle
HHV	higher heating value
L-BEV	light-duty battery electric vehicle
L-FCEV	light-duty fuel cell electric vehicle
LHV	lower heating value
LPG	liquefied petroleum gas
LTV	light traction vehicle
MCFC	molten carbonate fuel cell
MEA	membrane electrode assembly
PAFC	phosphoric acid fuel cell
PEMFC	polymer electrolyte membrane fuel cell
PGM	platinum group metals
PV	photovoltaic
RAPS	remote-area power supply
SOFC	solid oxide fuel cell
UAV	unmanned aerial vehicle

1. Introduction

A fuel cell is an electrochemical device that converts the chemical energy of a fuel directly into electrical energy. The one-step (from chemical to electrical energy) nature of this process, in comparison to the multi-step (e.g. from chemical to thermal to mechanical to electrical energy) processes involved in combustion-based heat engines, offers several unique advantages. For instance, the current combustion-based energy generation technologies are very harmful to the environment and are predominantly contributing to many global concerns, such as climate change, ozone layer depletion, acidic rains, and thus, the consistent reduction in the vegetation cover. Furthermore, these technologies depend on the finite and dwindling world supplies of fossil fuels.

Fuel cells, on the other hand, provide an efficient and clean mechanism for energy conversion. Additionally, fuel cells are compatible with renewable sources and modern energy carriers (i.e., hydrogen) for sustainable development and energy security. As a result, they are regarded as the energy conversion devices of the future. The static nature of fuel cells also means quiet operation without noise or vibration, while their inherent modularity allows for simple construction and a diverse range of applications in portable, stationary, and transportation power generation. In short, fuel cells provide a cleaner, more efficient, and possibly the most flexible chemical-to-electrical energy conversion.

Polymer electrolyte membrane, also proton exchange membrane, fuel cells (PEMFC) in particular are one of the most promising types already in the early commercialization stage. Nonetheless, further development and research are required in order to reduce their costs, enhance their durability, and further optimize and improve their performance. Most of the research currently being conducted on PEMFCs is on the individual cell-level and the general system-level. Stack-level research, on the other hand, is an area that requires further research and development.

A proper understanding of the principles of fuel cell operation combined with a current outlook of the fuel cell industry are vital for overcoming current obstacles and the general advancement of fuel cell technology. Nevertheless, fuel cells are an interdisciplinary science in which electrochemistry, thermodynamics, engineering economics, material science and engineering, and electrical engineering all combine; making this a difficult task. This paper provides an up-to-date overlook of the fuel cell industry coupled with a concise digest of fuel cell operation principles as a contribution to the ongoing efforts to promote and commercialize fuel cells. We will often attempt to highlight the relations between a fuel cell′s principals of operation, features and advantages, and areas of applications throughout the manuscript. This relation between principals, features, and applications is outlined in Fig. 1.

2. An overview of fundamentals

A fuel cell is composed of three active components: a fuel electrode (anode), an oxidant electrode (cathode), and an electrolyte sandwiched between them. The electrodes consist of a porous



Principal of Operation	Features
Electrochemical Energy Conversion	✓ High and Consistent Efficiency ✓ Reduced/Eliminated Harmful Emissions ✓ High Energy Density ✓ Prompt Load-Following ✓ Reduced/Eliminated Noise
Fewer Energy Transformations	✓ High and Consistent Efficiency ✓ Reduced/Eliminated Harmful Emissions ✓ Prompt Load-Following
Runs as Long as Fuel is Supplied	✓ Long Operational Cycles ✓ High Energy Density
Expansion by Adding Cells to a Stack and/or Stacks to a System	✓ Modularity ✓ High Integrability with Renewable Sources
Runs Best on Pure Hydrogen	✓ Reduced/Eliminated Harmful Emissions ✓ High Integrability with Renewable Sources
Static Operation with No Dynamic Parts	✓ Modularity ✓ Reduced/Eliminated Noise
Fuel Reformation Fueling Option	✓ Reduced/Eliminated Harmful Emissions ✓ Long Operational Cycles ✓ Fuel Flexibility
Direct Alcohol Fueling Option	✓ Long Operational Cycles ✓ Prompt Load-Following ✓ Fuel Flexibility

Feature	Application Areas
High and Consistent Efficiency	✓ Propulsion Systems ✓ Light Traction Vehicles ✓ Auxiliary Power Units ✓ Distributed Generation
Reduced/Eliminated Harmful Emissions	✓ Propulsion Systems ✓ Light Traction Vehicles ✓ Auxiliary Power Units ✓ Distributed Generation
Long Operational Cycles	✓ Portable Applications ✓ Propulsion Systems ✓ Light Traction Vehicles ✓ Emergency Back-Up
High Energy Density	✓ Portable Applications ✓ Propulsion Systems ✓ Light Traction Vehicles ✓ Emergency Back-Up
Prompt Load-Following	✓ Propulsion Systems ✓ Light Traction Vehicles ✓ Auxiliary Power Units ✓ Distributed Generation
Modularity	✓ Portable Applications ✓ Auxiliary Power Units ✓ Distributed Generation
Reduced/Eliminated Noise	✓ Propulsion Systems ✓ Light Traction Vehicles ✓ Auxiliary Power Units ✓ Distributed Generation
Fuel Flexibility	✓ Portable Applications ✓ Distributed Generation ✓ Emergency Back-Up
High Integrability with Renewable Sources	✓ Propulsion Systems ✓ Distributed Generation

Fig. 1. Outline of the relations between a fuel cell's principals of operation, advantages and features, and main areas of application.

material that is covered with a layer of catalyst (often platinum in PEMFCs). Fig. 2 illustrates the basic operational processes within a typical PEMFC [1]. Molecular hydrogen (H_2) is delivered from a gas-flow stream to the anode where it reacts electrochemically. The hydrogen is oxidized to produce hydrogen ions and electrons, as shown in Fig. 2, per the following equation:

$$H_2 \Rightarrow 2H^+ + 2e^- \quad (1)$$

The hydrogen ions migrate through the acidic electrolyte while the electrons are forced through an external circuit all the way to the cathode. At the cathode, the electrons and the hydrogen ions react with the oxygen supplied from an external gas-flow stream to form water, as shown in Fig. 2, per the following equation:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \Rightarrow H_2O \quad (2)$$

The overall reaction in the fuel cell produces water, heat, and electrical work as follows:

$$H_2 + \frac{1}{2}O_2 \Rightarrow H_2O + W_{ele} + Q_{heat} \quad (3)$$

The heat and water by-products must be continuously removed in order to maintain continuous isothermal operation for ideal electric power generation. Hence, water and thermal management are key areas in the efficient design and operation of fuel cells.

2.1. History

Research and development that eventually led to a functional fuel cell goes back to the early 1800s. Sir William Grove, a chemist and patent lawyer, is broadly considered to be the father of fuel cell science due to his famous water electrolyzer/fuel cell experimental demonstration. Sir William Grove used his background of electrolysis to conceptualize a reverse process that could be used to generate electricity. Based on this hypothesis, Grove succeeded in building a device that combines hydrogen and oxygen to produce electricity (instead of separating them using electricity). The device, originally labeled a gas battery, came to be known as a fuel cell. Further research continued into the twentieth century. In 1959, Francis Thomas Bacon, an English engineer, demonstrated the first fully-operational fuel cell. His work was impressive enough to get licensed and adopted by NASA [2]. PEMFCs and alkaline fuel cells (AFCs), in particular, were practically used by NASA in the 1960s as part of the Gemini and Apollo manned space programs. The NASA fuel cells were customized, non-commercial, experienced several malfunctions, and used pure oxygen and hydrogen as an oxidant and fuel, respectively. Fuel cells nowadays; however, are used in transportation, stationary, and portable

applications; are gradually being adopted by the public and private sectors; are becoming more reliable and durable for long-term operation; and can function using air and reformation-based hydrogen as an oxidant and fuel, respectively. Table 1 highlights the main milestones in the history of fuel cells.

2.2. Competing technologies

Fig. 3 shows a very interesting comparison between the main energy conversion devices in the market today [3]. It shows the typical exergy efficiencies of photovoltaic panels, thermal solar power plants, waste incineration, gas turbines, diesel engines, gas engines, Rankin cycles, combined Rankin–Brayton cycles, nuclear power plants, wind turbines, hydroelectric plants, in addition to fuel cells. As evident from the figure, fuel cells have one of the highest exergy efficiencies among the competing energy conversion devices. Tables 2–4, technoeconomically compare fuel cells to their competing technologies in the portable, stationary, and transportation sectors, respectively. The comparisons reveal that with respect to competing technologies, fuel cells have an advantage in both gravimetric and volumetric energy densities in the portable sector; have high efficiencies and capacity factors in the stationary sector; and offer high efficiencies and fuel flexibilities in the transportation sector. As such, it becomes clear that bringing down the investment cost of fuel cells in order to relatively level the competition field with other power technologies is probably the most vital challenge fuel cells need to overcome in order to become economically-feasible power generation alternatives. In the remainder of this section, we will further discuss the differences and similarities between fuel cells and their two closest energy competitors; namely—heat engines and batteries.

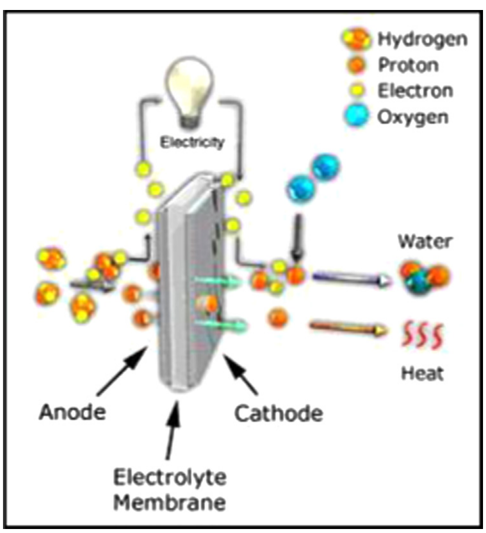


Fig. 2. Typical PEM fuel cell operation [1].

Both fuel cells and heat engines typically use a hydrogen-based fluid and atmospheric air as the fuel and oxidant, respectively. However, fuel cells combine the fuel and oxidant electrochemically, while heat engines combine the fuel and oxidant via combustion. Additionally, fuel cells produce electrical work directly from chemical energy. While in the case of heat engines, producing electricity is a multi-step process that involves combustion to produce thermal energy from the internal chemical energy of the fuel. Then this thermal energy is converted into mechanical energy, and finally this mechanical energy is converted into electrical energy through the use of a generator. Generally, as the number of energy conversion processes increases in a certain device, the overall system efficiency of the device decreases. Fuel cells, in comparison to heat engines, produce fewer-to-zero pollutants and have higher theoretical and practical efficiencies. While on the other hand, heat engines are limited by the Carnot efficiency between their low and the high working temperatures and are responsible for a significant portion of the world's pollution. Finally, fuel cell stacks are static devices that operate with almost no noise or vibrations (as will be discussed in Section 3.5). Heat engines, on the other hand, have many dynamic components (e.g., pistons and gears) that produce a lot of noise and vibrations. This dynamic nature of heat engines limits their applications.

Fuel cells and batteries are quite similar in the sense that they are both electrochemical cells that consist of an electrolyte sandwiched between two electrodes. They both use internal oxidation–reduction reactions to convert the chemical energy content of a fuel to DC electricity. However, the composition and role of the electrodes differ significantly between the two energy devices. The electrodes in a battery are typically metals (e.g., zinc, lead, or lithium) immersed in mild acids. In fuel cells, the electrodes (i.e., catalyst layer and gas diffusion layer) typically consist of a proton-conducting media, carbon-supported catalyst, and electron-conducting fibers. Batteries are used as energy storage and conversion devices, while fuel cells are used for energy conversion only. A battery uses the chemical energy stored in its electrodes to fuel the electrochemical reactions that give us electricity at a specified potential difference. Thus, a battery has a limited lifetime and can only function as long as the electrodes' material is not yet depleted. Upon depletion of the electrodes'

Table 1
Main milestones in the history of fuel cells.

Year(s)	Milestone
1839	W.R. Grove and C.F. Schönbein separately demonstrate the principals of a hydrogen fuel cell
1889	L. Mond and C. Langer develop porous electrodes, identify carbon monoxide poisoning, and generate hydrogen from coal
1893	F.W. Ostwald describes the functions of different components and explains the fundamental electrochemistry of fuel cells
1896	W.W. Jacques builds the first fuel cell with a practical application
1933–1959	F.T. Bacon develops AFC technology
1937–1939	E. Baur and H. Preis develop SOFC technology
1950	Teflon is used with platinum/acid and carbon/alkaline fuel cells
1955–1958	T. Grubb and L. Niedrach develop PEMFC technology at General Electric
1958–1961	G.H.J. Broers and J.A.A. Ketelaar develop MCFC technology
1960	NASA uses AFC technology based on Bacon's work in its Apollo space program
1961	G.V. Elmore and H.A. Tanner experiment with and develop PAFC technology
1962–1966	The PEMFC developed by General Electric is used in NASA's Gemini space program
1968	DuPont introduces Nafion®
1992	Jet Propulsion Laboratory develops DMFC technology
1990s	Worldwide extensive research on all fuel cell types with a focus on PEMFCs
2000s	Early commercialization of fuel cells

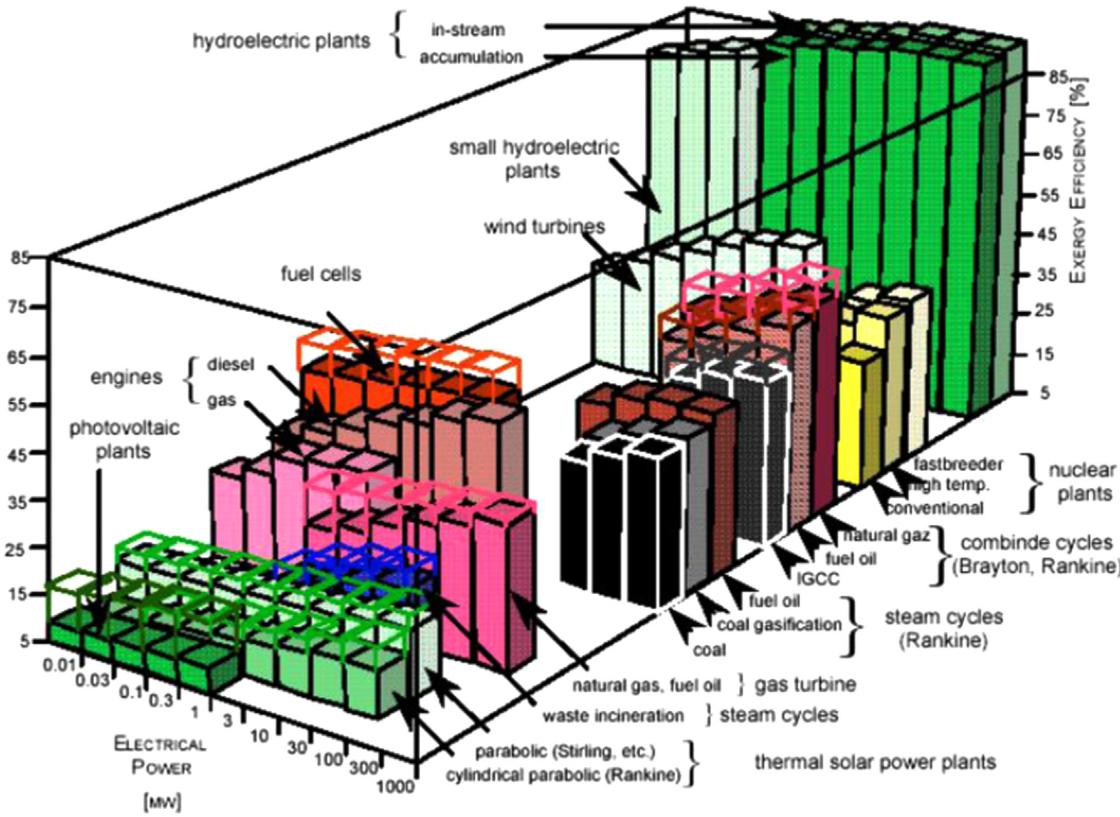


Fig. 3. Exergy efficiencies of main energy conversion devices [3].

Table 2
Technoeconomic comparison between fuel cells and their competitors in the portable power sector (adapted from [5]).

Portable power technology	Gravimetric energy density (Wh/kg)	Volumetric energy density (Wh/L)	Power density (W/kg)	Capital cost ($/kWh)
Direct methanol fuel cell	> 1000	700–1000	100–200	200[a]
Lead-acid battery	20–50	50–100	150–300	70
Nickel–cadmium battery	40–60	75–150	150–200	300
Nickel–metal hydride battery	60–100	100–250	200–300	300–500
Lithium-ion battery	100–160	200–300	200–400	200–700
Flywheel	50–400	200	200–400	400–800
Ultracapacitor	10	10	500–10,000	20,000

[a] In $/kW.

Table 3
Technoeconomic comparison between fuel cells and their competitors in the stationary power/CHP sector (adapted from [5]).

Stationary power/CHP technology	Power level (MW)	Efficiency[a] (%)	Lifetime (years)	Capital cost ($/kW)	Capacity factor (%)
Phosphoric acid fuel cell	0.2–10	30–45	5–20	1500	Up to 95
MCFC/gas turbine hybrid	0.1–100	55–65	5–20	1000	Up to 95
SOFC/gas turbine hybrid	0.1–100	55–65	5–20	1000	Up to 95
Steam cycle (coal)	10–1000	33–40	> 20	1300–2000	60–90
Integrated gasification combined cycle	10–1000	43–47	> 20	1500–2000	75–90
Gas turbine cycle (natural gas)	0.03–1000	30–40	> 20	500–800	Up to 95
Combined gas turbine cycle (natural gas)	50–1000	45–60	> 20	500–1000	Up to 95
Microturbine	0.01–0.5	15–30	5–10	800–1500	80–95
Nuclear	500–1400	32	> 20	1500–2500	70–90
Hydroelectric	0.1–2000	65–90	> 40	1500–3500	40–50
Wind turbine	0.1–10	20–50	20	1000–3000	20–40
Geothermal	1–200	5–20	> 20	700–1500	Up to 95
Solar photovoltaic	0.001–1	10–15	15–25	2000–4000	< 25

[a] From energy input to electrical output.

material, a battery must be either replaced (in case of a disposable battery) or recharged (by using an electric current to reform dissolved metals on the electrodes). In a fuel cell; however, the reactants are supplied from a separate storage device and the internal components are not used up in the electrochemical reactions. Thus, theoretically, a fuel cell can keep running as long as the reactants are sufficiently

Table 4
Technoeconomic comparison between fuel cells and their competitors in the transportation propulsion sector (adapted from [5]).

Transportation propulsion technology	Power level (kW)	Efficiency[a] (%)	Specific power (kW/kg)	Power density (kW/L)	Vehicle range (km)	Capital cost ($/kW)
Proton exchange membrane fuel cell (on-board fuel processing)	10–300	40–45	400–1000	600–2000	350–500	100
Proton exchange membrane fuel cell (off-board hydrogen)	10–300	50–55	400–1000	600–2000	200–300	100
Gasoline engine	10–300	15–25	> 1000	> 1000	600	20–50
Diesel engine	10–200	30–35	> 1000	> 1000	800	20–50
Diesel engine/battery hybrid	50–100	45	> 1000	> 1000	> 800	50–80
Gasoline engine/battery hybrid	10–100	40–50	> 1000	> 1000	> 800	50–80
Lead-acid or nickel-metal hydride battery	10–100	65	100–400	250–750	100–300	> 100

[a] From energy input to electrical output.

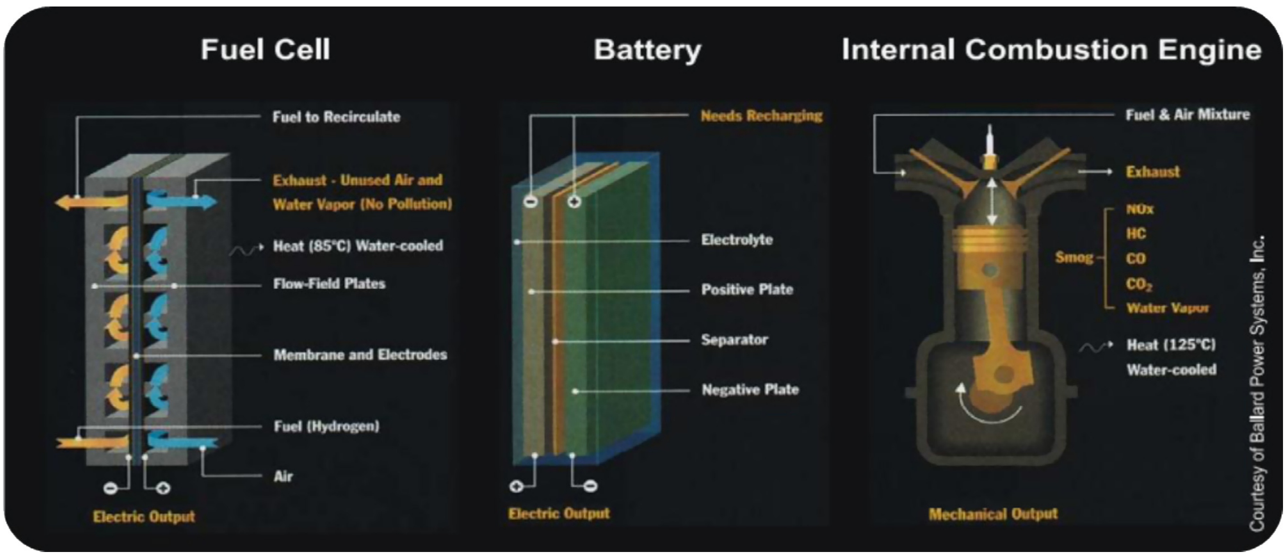


Fig. 4. Fuel cell, battery, and internal combustion heat engine general structures [6].

Table 5
Summary of the similarities and differences between fuel cells, batteries, and heat engines.

Comparison	Fuel cell	Battery	Heat engine
Function	Energy conversion	Energy storage & conversion	Energy conversion
Technology	Electrochemical reactions	Electrochemical reactions	Combustion
Typical fuel	Usually pure hydrogen	Stored chemicals	Gasoline, diesel
Useful output	DC electricity	DC electricity	Mechanical power
Main advantages	High efficiency	High efficiency	High maturity
	Reduced harmful emissions	High maturity	Low cost
Main disadvantages	High cost	Low operational cycles	Significant harmful emissions
	Low durability	Low durability	Low efficiency

supplied and the products are properly removed. As a result, an operational fuel cell system requires a fuel storage mechanism and an oxidant supply mechanism to be incorporated within it. Moreover, when the battery is idle, electrochemical reactions that deteriorate the battery occur very slowly, reducing the lifetime of the battery. Rechargeable batteries suffer from many technical issues that limit their applications; some of these issues include power storage and retrieval potential, depth of charge, and number of charge/discharge cycles [4]. In the case of fuel cells this is not an issue. Additionally, there is no leakage or corrosion of cell components when the fuel cell is not in use, unlike with batteries [5]. Fig. 4 [6] and Table 5 summarize the differences and similarities between fuel cells, heat engines, and batteries.

2.3. Types

There are many types of fuel cells available in the market today. Fuel cells are conventionally categorized according to their electrolyte material. They differ in their power outputs, operating temperatures, electrical efficiencies, and typical applications. PEMFCs have the largest range of applications as they are extremely flexible. PEMFCs are the most promising candidates for transport applications due to their high power density, fast start-up time, high efficiency, low operating temperature, and easy and safe handling. However, PEMFCs are still too expensive to be competitive or economically-feasible. AFCs have the best performance when operating on pure hydrogen and oxygen, yet their

Table 6
Fuel cell types according to electrolyte.

Fuel cell type	Typical electrolyte	Typical anode/ cathode catalysts[a]	Typical interconnect material	Typical fuel	Charge carrier[a]	Major contaminants[a]	Operation temperature (°C)	Specific advantages	Specific disadvantages	Electrical efficiency (%)	Technological maturity[b]	Research activity[c]
Low-temperature proton exchange membrane	• Solid Nafion®	• Anode: Platinum supported on carbon • Cathode: Platinum supported on carbon	Graphite	Hydrogen	H^+	• Carbon monoxide (CO) • Hydrogen sulfide (H_2S)	60–80	• Highly modular for most applications • High power density • Compact structure • Rapid start-up due to low temperature operation • Excellent dynamic response	• Complex water and thermal management • Low-grade heat • High sensitivity to contaminants • Expensive catalyst	40–60	4	H
High-temperature proton exchange membrane	• Solid composite Nafion® • Polybenzimidazole (PBI) doped in phosphoric acid	• Anode: Platinum–Ruthenium supported on carbon • Cathode: Platinum–Ruthenium supported on carbon	Graphite	Hydrogen	H^+	• Carbon Monoxide (CO)	110–180	• Simple water management • Simple thermal management • Accelerated reaction kinetics • High-grade heat • High tolerance to contaminants	• Accelerated stack degradation • Humidification issues • Expensive catalyst	50–60	3	M
Solid oxide	• Solid yttria-stabilized zirconia (YSZ)	• Anode: Nickel–YSZ composite • Cathode: Strontium-doped lanthanum manganite (LSM)	Ceramics	Methane	O^{2-}	• Sulfides	800–1000	• High electrical efficiencies • High-grade heat • High tolerance to contaminants • Possibility of internal reforming • Eliminated electrolyte issues • Fuel flexibility • Inexpensive catalyst	• Slow start-up • Low power density • Strict material requirements • High thermal stresses • Sealing issues • Durability issues • High manufacturing costs	55–65	3	H
Molten carbonate	• Liquid alkali carbonate (Li_2CO_3, Na_2CO_3, K_2CO_3) in Lithium aluminate ($LiAlO_2$)	• Anode: Nickel Chromium (NiCr) • Cathode: Lithiated nickel oxide (NiO)	Stainless steel	Methane	CO_3^{2-}	• Sulfides • Halides	600–700	• High electrical efficiencies • High-grade heat • High tolerance to contaminants • Possibility of internal reforming • Less strict material requirements • Fuel flexibility • Inexpensive catalyst	• Slow start-up • Low power density • Electrolyte corrosion and evaporative losses • Corrosion of metallic parts • Air crossover • Catalyst dissolution in electrolyte • Cathode carbon dioxide (CO_2) injection requirement	55–65	4	H

Phosphoric Acid	• Concentrated liquid phosphoric acid (H_3PO_4) in silicon carbide (SiC)	• Anode: Platinum supported on carbon • Cathode: Platinum supported on carbon	Graphite	Hydrogen	H^+	• Carbon monoxide (CO) • Siloxane • Hydrogen sulfide (H_2S)	160–220	• Technologically mature and reliable • Simple water management • Good tolerance to contaminants • High-grade heat	• Relatively slow start-up • Low power density • High sensitivity to contaminants • Expensive auxiliary systems • Low electrical efficiencies • Relatively large system size • Electrolyte acid loss • Expensive catalyst • High cost	36–45	5	M
Alkaline	• Potassium hydroxide (KOH) water solution • Anion exchange membrane (AEM)	• Anode: Nickel • Cathode: Silver supported on carbon	Metallic wires	Hydrogen	OH^-	• Carbon dioxide (CO_2)	Below zero–230	• High electric efficiency due to fast reduction reaction kinetics • Wide range of operation temperature and pressure • Inexpensive catalyst • Catalyst flexibility • Relatively low costs	• Extremely high sensitivity to contaminants • Pure hydrogen and oxygen required for operation • Low power density • Highly corrosive electrolyte leads to sealing issues • Complex and expensive electrolyte management for mobile electrolyte systems	60–70	5	L
Direct methanol	• Solid Nafion®	• Anode: Platinum–Ruthenium supported on carbon • Cathode: Platinum supported on carbon	Graphite	Liquid methanol–water solution	H^+	• Carbon monoxide (CO)	Ambient-110	• Compact size • Simple system • High fuel volumetric energy density • Easy fuel storage and delivery • Simple thermal management for liquid methanol systems	• Low cell voltage and efficiency due to poor anode kinetics • Low power density • Lack of efficient catalysts for direct oxidation of methanol • Fuel and water crossover • Complex water management • High catalyst loading • High cost • Carbon dioxide (CO_2) removal system • Fuel toxicity	35–60	3	H
Direct ethanol	• Solid Nafion® • Alkaline media • Alkaline-Acid media	• Anode: Platinum–Ruthenium supported on carbon • Cathode: Platinum	Graphite	Liquid ethanol–water solution	H^+	• Carbon monoxide (CO)	Ambient-120	• Compact size • Environmentally-friendly fuel • High fuel volumetric energy density • Relatively low	• Low power density • High sensitivity to carbon monoxide (CO) • Low cell voltage and efficiency due to poor anode kinetics	20–40	2	L

Table 6 (*continued*)

Fuel cell type	Typical electrolyte	Typical anode/cathode catalysts[a]	Typical interconnect material	Typical fuel	Charge carrier[a]	Major contaminants[a]	Operation temperature (°C)	Specific advantages	Specific disadvantages	Electrical efficiency (%)	Technological maturity[b]	Research activity[c]
		supported on carbon						fuel toxicity • Relatively higher gravimetric energy density • Easy fuel storage and delivery • Simple thermal management	• Lack of efficient catalysts for direct oxidation of ethanol • High cost • Fuel and water crossover			
Direct ethylene glycol	• Solid Nafion® • Anion exchange membrane (AEM)	• Anode: Platinum supported on carbon • Cathode: Platinum supported on carbon	Graphite	Liquid ethylene glycol	H^+	• Carbon monoxide (CO)	Ambient-130	• Compact size • High fuel volumetric energy density • Low volatility due to low vapor pressure and high boiling point • Easy fuel storage and delivery • Simple thermal management • Simple water management • Existence of distribution infrastructure	• Low power density • Low cell voltage and efficiency due to poor anode kinetics • Lack of efficient catalysts for direct oxidation of ethylene glycol • Low fuel gravimetric energy density • Durability issues • High cost • Fuel crossover	20–40	2	L
Microbial	• Ion exchange membrane	• Anode: Biocatalyst supported on carbon • Cathode: Platinum supported on carbon	N/A	Any organic matter (e.g., glucose, acetate, waste-water)	H^+	• Bacterial contamination of cathode	20–60	• Fuel flexibility • Biocatalyst flexibility • No need for enzymatic catalysts isolation, extraction, and preparation • Relatively higher lifetime for biocatalysts • Capacity for self-regeneration of enzymes	• Electron transfer mechanisms from the metabolism in the microorganisms to the fuel cell anode is problematic • Relatively lower energy density due to using some of the energy for the microorganisms activity • Very low power density • Low columbic yield • Inflexible operation conditions	15–65[d]	1	M

Enzymatic	• Membrane-less • Ion exchange membrane	• Anode: Biocatalyst supported on carbon • Cathode: Biocatalyst supported on carbon	N/A	Organic matters (e.g., glucose)	H^+	• Foreign physical and/or chemical exposure to enzymatic catalyst	20–40	• Capacity for miniaturization (e.g., for implantable medical micro-scale sensors and devices) • Structural simplicity • High response time	• Rapid decay of enzymatic catalyst due to operation in foreign environment • High susceptibility to enzymatic poisoning • Electron transfer mechanism from the reactive centers of the biocatalysts to the fuel cell electrodes is problematic • Immobilizing the enzymes is problematic • Low power density • Very low columbic yield • Low fuel flexibility • Inflexible operation conditions	30[d]	1	M
Direct carbon	• Solid yttria-stabilized zirconia (YSZ) • Molten carbonate • Molten hydroxide	• Anode: Graphite or carbon-based material • Cathode: Strontium-doped lanthanum manganite (LSM)	N/A	Solid carbon (e.g., coal, coke, biomass)	O^{2-}	• Ash • Sulfur	600–1000	• High electrical efficiency • High volumetric energy density • Fuel flexibility • No PM, NO_x, or SO_x emissions • Structural simplicity • High capacity for carbon sequestration	• Carbon dioxide (CO_2) emissions • Rapid material corrosion and degradation • Durability issues • Sensitivity to fuel impurities • Low power density	70–90	L	2
Direct borohydride	• Solid Nafion® • Anion exchange membrane (AEM)	• Anode: Gold, silver, nickel, or platinum supported on carbon • Cathode: Platinum supported on carbon	Graphite	Sodium borohydride ($NaBH_4$)	Na^+	• N/A	20–85	• Compact size • High fuel utilization efficiency • High fuel gravimetric hydrogen content • No carbon dioxide (CO_2) emissions • Low toxicity and environmentally-friendly operation	• Fuel crossover • High cost • Low power density • Lack of analytical modeling techniques due to unknown borohydride oxidation reaction mechanisms • Expensive catalyst • Chemical instability of membrane and catalyst • Inefficient cathodic reduction reaction • Inefficient anodic oxidation reaction due to hydrogen evolution from hydrolysis of borohydride and partial release of fuel electrons	40–50	M	2
Direct formic acid	• Solid Nafion®	• Anode: Palladium or platinum supported on carbon	N/A	Liquid formic acid (HCOOH)	H^+	• Carbon monoxide (CO)	30–60	• Improved anodic oxidation reaction kinetics • High fuel utilization	• Fuel toxicity • Components Corrosion issues • Low fuel gravimetric and volumetric	30–50	L	1

Table 6 (*continued*)

Fuel cell type	Typical electrolyte	Typical anode/cathode catalysts[a]	Typical interconnect material	Typical fuel	Charge carrier[a]	Major contaminants[a]	Operation temperature (°C)	Specific advantages	Specific disadvantages	Electrical efficiency (%)	Technological maturity[b]	Research activity[c]
		• Cathode: platinum supported on carbon						efficiency • Limited fuel crossover • Easy fuel storage and delivery • High power density • No water required at the anode for oxidation reaction • Compact size and structural simplicity	energy density • High fuel cost • Low temperature operation			

[a] For the first typical electrolyte only.
[b] With 1 being lowest and 5 highest technological maturity relative to other fuel cell types.
[c] H: High; M: Moderate; L: Low.
[d] Columbic efficiency: The ratio of the coulombs transferred from the substrate to the anode to the coulombs produced if all the substrate is oxidized.

intolerance to impurities (especially carbon oxides) and short lifetimes hinder their role for terrestrial applications (they are predominantly used for extraterrestrial purposes). Phosphoric acid fuel cells (PAFCs) are possibly the most commercially-developed fuel cells operating at intermediate temperatures. PAFCs are used for combined-heat-and-power (CHP) applications with high energy efficiencies. Molten carbonate fuel cells (MCFCs) and solid oxide fuel cells (SOFCs) are high-temperature fuel cells appropriate for cogeneration and combined cycle systems. MCFCs have the highest energy efficiency attainable from methane-to-electricity conversion in the size range of 250 kW to 20 MW, while SOFCs are best suited for base-load utility applications operating on coal-based gasses. Table 6 summarizes the main differences between the most common fuel cell types available in the market or still in the development stage.

3. Characteristics and features

Fuel cells have many inherent advantages over conventional combustion-based systems, making them one of the strongest candidates to be the energy conversion device of the future. They also have some inherent disadvantages that require further research and development to overcome them. We will elaborate on fuel cells′ advantages and challenges in Sections 3.1–3.6 and Sections 3.7–3.12, respectively.

3.1. Reduced harmful emissions

The only products from a fuel cell stack fueled by hydrogen are water, heat, and DC electricity. And with the exception of controllable NO_x emissions from high-temperature fuel cells, a hydrogen fuel cell stack is emissions-free. However, the clean nature of a fuel cell depends on the production path of its fuel (e.g. hydrogen). For instance, the products of a complete fuel cell system that includes a fuel reformation stage include greenhouse emissions (e.g., CO and CO_2). When the hydrogen supplied to the fuel cell is pure (i.e., not reformation-based hydrogen which is always contaminated with CO_x), the durability and reliability of the fuel cell significantly improve in comparison to when we run the fuel cell on reformation-based hydrogen. This is one of the most important advantages of fuel cells in comparison to heat engines, i.e., fuel cells are inherently clean energy converters that ideally run on pure hydrogen. This fact is actually pressingly driving researchers and the industry to develop efficient and renewable-based hydrogen generation technologies based on clean water electrolysis to replace the conventional reformation-based ones. Systems that integrate renewable-based hydrogen generation with fuel cells are genuinely clean energy generation and conversion systems that resemble what the energy industry is striving to achieve. It is worth mentioning that when we take into consideration the emissions from the fossil fuel reformation process, some heat engine systems appear to be less polluting than fuel cell systems (see Ref. [7]). For non-renewable energy based water electrolysis, the emissions and energy used for the electrolysis process make it more harmful to the environment than conventional combustion heat engines. Moreover, it is economically unfeasible since any fossil energy used for hydrogen production is going to be always more than the energy content of hydrogen. According to studies by Argonne National Laboratory [8], 3,000,000–3,500,000 BTUs of fossil energy are used for the production of 1,000,000 BTUs of hydrogen through fossil energy-based water electrolysis. This only stresses the significance of the aforementioned conclusions regarding using renewable-based water electrolysis for hydrogen production.

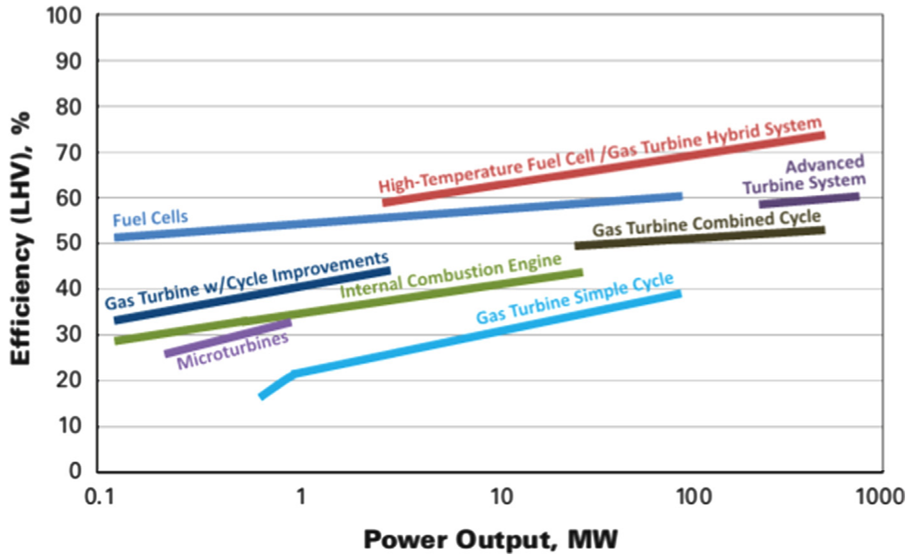


Fig. 5. Efficiency comparison between fuel cells and other energy conversion devices with respect to system size [9].

3.2. High efficiency

The amount of heat that could be converted to useful work in a heat engine is limited by the ideal reversible Carnot efficiency, given by the following equation:

$$\eta_{Carnot} = \frac{T_i - T_e}{T_i} \tag{4}$$

where T_i is the absolute temperature at the engine inlet and T_e is the absolute temperature at the engine exit. However, a fuel cell is not limited by the Carnot efficiency since a fuel cell is an electrochemical device that undergoes isothermal oxidation instead of combustion oxidation. The maximum conversion efficiency of a fuel cell is bounded by the chemical energy content of the fuel and is found by (will be further discussed in Section 7.1):

$$\eta_{rev} = \frac{\Delta G_f}{\Delta H_f} \tag{5}$$

where ΔG_f is the change in Gibbs free energy of formation during the reactions and ΔH_f is the change in the enthalpy of formation (using lower heating value (LHV) or higher heating value (HHV)). Fig. 5 illustrates the efficiency of fuel cells and other energy conversion devices with respect to system power output [9]. In light vehicles, for instance, the efficiency of a fuel cell-powered car is nearly twice the efficiency of an internal combustion engine-powered car. Part of the reason why fuel cells have higher overall efficiencies compared to combustion-based energy conversion devices is illustrated in Fig. 6. The fact that the number of energy transformations that occur within a fuel cell stack is less than that of any combustion-based device, when the required output is electricity, plays a significant role. This is because losses are associated with each energy transformation process; thus, the overall efficiency of a system generally decreases as the number of energy transformations increases. As evident from Fig. 6, fuel cells have an advantage in the number of energy transformations over heat engines when the desired output is electrical power. However, fuel cells are on a par with batteries and heat engines in the number of energy transformations when the desired output is mechanical work.

3.3. Modularity

Fuel cells have excellent modularity. In principle, changing the number of cells-per-stack and/or stacks-per-system (see Section 6) allows us to control the power output of any fuel cell system. Unlike combustion-based devices, a fuel cell's efficiency does not vary much with system size (see Fig. 5) or load factor. In fact, as opposed to conventional power plants, fuel cells have higher efficiencies at part loads compared to full loads (as will be shown in Section 7.5). This would prove advantageous in large-scale fuel cell systems that would normally run on part-load instead of full-load. Additionally, the high modularity of fuel cells means that smaller fuel cell systems have similar efficiencies to larger systems. This feature greatly facilitates the future integration of fuel cells (and hydrogen systems in general) in small-scale distributed generation systems, which hold a great potential in the power generation industry. It is worth noting; however, that reformation processors are not as modular as fuel cell stacks. This presents another reason to shift to renewable-based hydrogen production technology.

3.4. Prompt load-following

Fuel cell systems generally have very good dynamic load-following characteristics [10,11]. This is partially due to the prompt nature of the electrochemical reactions that occur within a fuel cell. Again, when the fuel cell system includes a fuel reformation stage, the load-following ability of the system noticeably decreases as a result of the slower nature of the reformation process.

3.5. Static nature

Due to its electrochemical nature, a fuel cell stack is a static silent device. This is a very important feature that promotes the use of fuel cells for auxiliary power and distributed generation applications in addition to portable applications that require silent-operation (as will be shown in Section 4). The fact that a fuel cell system has very few dynamic parts (and hence, almost no vibrations) makes fuel cells design, manufacturing, assembly, operation, and analysis simpler than that of heat engines. Nevertheless, for fuel cell systems that use compressors instead of blowers for the oxidant supply, noise levels can noticeably increase. As such, fuel cell designers tend to avoid using compressors due to their high parasitic load, noise production, cost, weight, volume, and complexity relative to fans and blowers. For instance, in a conventional urban bus, most of the noise is generated from the diesel engine. A fuel cell stack, on the other hand, is a completely silent device. As such, the noise level from a fuel cell bus

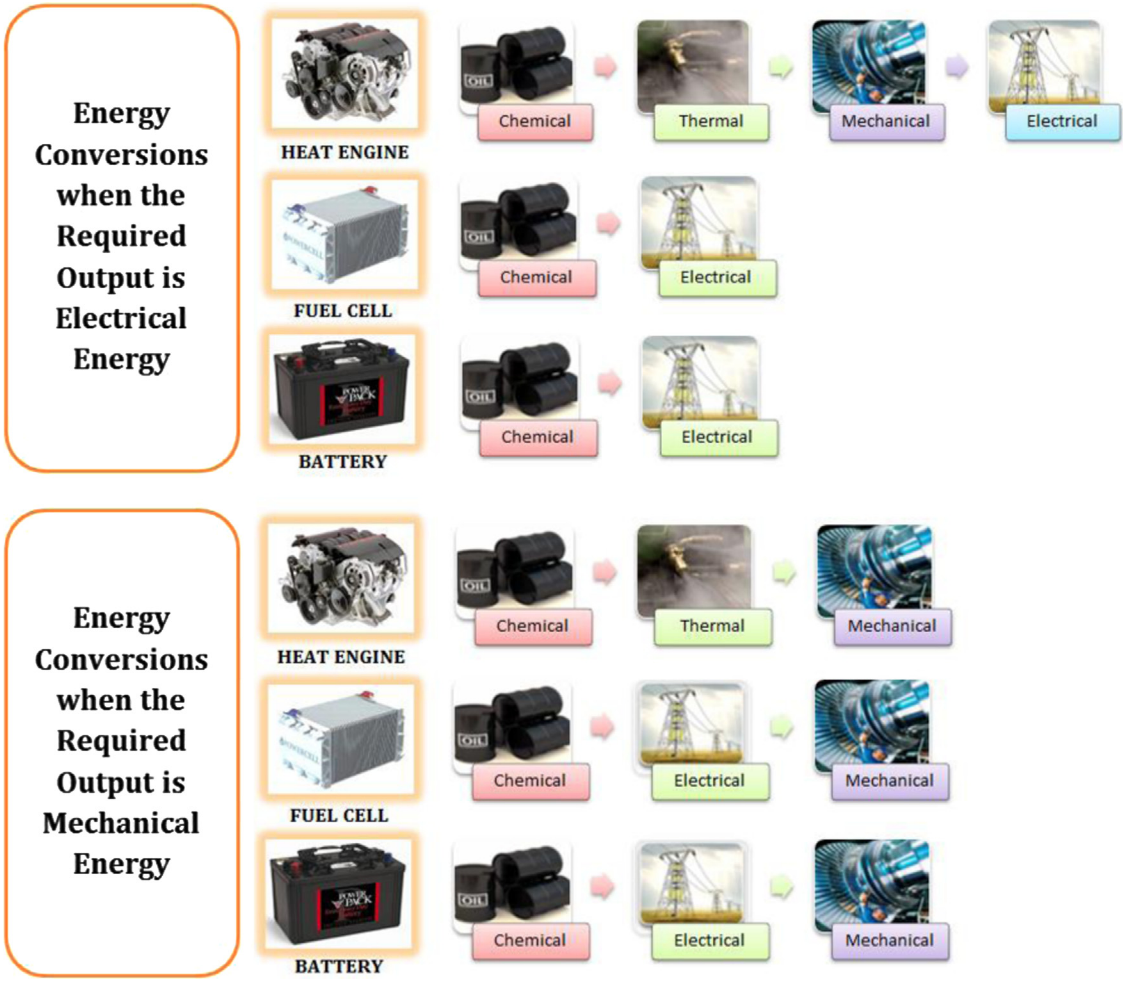


Fig. 6. Energy transformations in fuel cells, batteries, and heat engines.

could be significantly lower than a conventional bus provided that the fuel cell system's balance-of-plant (BoP) components are reasonably quiet. A study that compared a PAFC bus with diesel engine buses found the noise generated at 2.75 m from the former is at a maximum of 73 dB(A) while it ranges between 82 and 87 dB(A) for the latter [12]. The noise reduction in PAFC-based buses is greater than PEMFC-based buses [12]. This is due to the fact that, unlike PEMFCs, a PAFC operates at near-ambient pressures and does not require the use of a compressor. This, again, emphasizes the importance of developing efficient and simpler BoP components in a fuel cell system. A similar study found a PEMFC bus to generate 70.5 dB(A) compared to 76.5 dB(A) for a natural gas bus and 77.5 dB(A) for diesel buses at 10 m [13]. The static nature of a fuel cell also reflects on its low maintenance requirements in comparison to competing technologies such as heat engines, wind turbines, and concentrated solar power (CSP) plants.

3.6. *Range of applications and fuel flexibility*

Fuel cells have diverse applications ranging from micro-fuel cells with less than 1 W power outputs to multi-MW prime power generation plants. This is attributed to their modularity, static nature, and variety of fuel cell types. This qualifies fuel cells to replace batteries used in consumer electronics and auxiliary vehicular power. These same properties also qualify a fuel cell to replace heat engines used in transportation and power generation. Fuel cells are also highly integrable to most renewable power generation technologies. Fuel cells that operate on low-temperature ranges require short warm-up times, which is important for portable and emergency power applications. While for fuel cells that operate on medium- to high-temperature ranges, utilization of waste heat both increases the overall efficiency of the system and provides an additional form of power output useful for domestic hot water (DHW) and space heating residential applications or CHP industrial-level applications. Fuels for a reformation-based fuel cell system include methanol, methane, and hydrocarbons such as natural gas and propane. These fuels are converted into hydrogen through a fuel reformation process. Alternatively, direct alcohol fuel cells (e.g. direct methanol fuel cells) can run directly on an alcohol. And even though fuel cells run best on hydrogen generated from water electrolysis, a fuel cell system with natural gas reformation also possesses favorable features to conventional technologies.

Fuel cells have been rapidly developing during the past 20 years due to the revived interest in them that started during the 1990s. However, they are still not at the widespread-commercialization stage due to many technical and socio-political factors, with cost and durability being the main hurdles that prevent fuel cells from becoming economically-competitive in the energy market. The main challenges are detailed as follows.

3.7. *High cost*

Fuel cells are expensive. Experts estimate that the cost-per-kW generated using fuel cells has to drop by a factor of 10 for fuel cells to enter the energy market. Three main reasons behind the current high cost of fuel cell stacks are: the dependence on platinum-based catalysts, delicate membrane fabrication techniques, and the coating and plate material of bipolar plates. While from a system-level

perspective, the BoP components such as fuel supply and storage subsystems, pumps, blowers, power and control electronics, and compressors constitute about half the cost of a typical complete fuel cell system. More specifically, whether renewable- or hydrocarbon-based, the current hydrogen production BoP equipment are far from being cost-effective. Technological advances in contaminate removal for hydrocarbon-based technologies are essential if the cost of fuel cell systems is to meet planned targets. Nevertheless, if fuel cells successfully enter the mass production stage, their costs are expected to significantly drop and become consumer-affordable due to the fact that manufacturing and assembly of fuel cells is generally less demanding than typical competing technologies, such as heat engines.

3.8. Low durability

The durability of fuel cells needs to be increased by about five times the current rates (e.g., at least 60,000 h for the stationary distributed generation sector) in order for fuel cells to present a long-term reliable alternative to the current power generation technologies available in the market (more on this in Section 5). The degradation mechanisms and failure modes within the fuel cell components and the mitigation measures that could be taken to prevent failure need to be examined and tested. Contamination mechanisms in fuel cells due to air pollutants and fuel impurities need to be carefully addressed to resolve the fuel cell durability issue.

3.9. Hydrogen infrastructure

One of the biggest challenges that face fuel cells commercialization is the fact that we are still producing 96% of the world's hydrogen from hydrocarbon reformation processes [14]. Producing hydrogen from fossil fuels (mainly natural gas) and then using it in fuel cells is economically disadvantageous since the cost-per-kWh delivered from hydrogen generated from a fossil fuel is higher than the cost-per-kWh if we were to directly use the fossil fuel. Thus, promoting renewable-based hydrogen is the only viable solution to help the shift from a fossil-based economy to a renewable-based, hydrogen-facilitated economy. Moreover, development of hydrogen storage mechanisms that provide high energy density per mass and volume whilst maintaining a reasonable cost is the second half of the hydrogen infrastructure dilemma. Any widely-adopted hydrogen storage technology will have to be completely safe since hydrogen is a very light and highly-flammable fuel that could easily leak from a regular container. Metal- and chemical-hydride storage technologies are proving to be safer and more efficient options than the traditional compressed gaseous and liquid hydrogen mechanisms. However, more research and development are needed to reduce the relatively high cost of the hydride storage technologies and to further improve their properties.

3.10. Water balance

Water transport (fundamentally discussed in Section 7.3) within a fuel cell is a function of water entering with inlet streams, water generated by the cathodic reaction, water migration from one component to another, and water exiting with exit streams. Generally speaking, a successful water management strategy would keep the membrane well-hydrated without causing water accumulation and blockage in any part of the MEA or flow fields. As such, maintaining this delicate water balance inside a PEMFC over different operation conditions and load requirements is a major technical difficulty the scientific community is required to fully address [15]. Flooding of the membrane; water accumulation in the pores and channels of the GDL and flow fields; dryness of the membrane; freezing of residual water inside the fuel cell; dependence between thermal, gases, and water management; and humidity of the feeding gases are all subtle and

Table 7
Summary of the main advantages and disadvantages of fuel cells.

Advantages	Disadvantages
Less/no pollution	Immature hydrogen infrastructure
Higher thermodynamic efficiency	Sensitivity to contaminants
Higher part-load efficiency	Expensive platinum catalysts
Modularity and scalability	Delicate thermal and water management
Excellent load response	Dependence on hydrocarbons reformation
Fewer energy transformations	Complex and expensive BoP components
Quiet and static	Long-term durability and stability issues
Water and cogeneration applications	Hydrogen safety concerns
Fuel flexibility	High investment cost-per-kW
Wide range of applications	Relatively large system size and weight

interdependent facets in the water management of a PEMFC [15–17]. Improper water management within a PEMFC leads to both performance loss and durability degradations [15,16] as a result of permanent membrane damage, low membrane ionic conductivity, non-homogeneous current density distribution, delamination of components, and reactants starvation. As such, water management strategies range from direct water injection to reactant gases recirculation [15]. The performance evaluation of a water management technique could be accomplished using empirical liquid water visualization or micro- and macro-scale numerical simulation [15]. Nonetheless, fundamental understanding and comprehensive models of water transport phenomena within a fuel cell are highly needed in order to develop optimized component designs, residual water removal methods, and MEA materials according to application requirements and operation conditions [16,17].

3.11. Parasitic load

The parasitic load required to run the auxiliary BoP components reduces the overall efficiency of the system. This is clearly evident when the power required to run auxiliary components such as air compressors, coolant pumps, hydrogen circulation pumps, etc. is included in the efficiency calculations (as will be shown in Section 7.5). Additionally, the weight and size of fuel cell systems will need to be reduced in order for fuel cells to become compatible with on-board transportation applications and small-scale portable applications.

3.12. Codes, standards, safety, and public awareness

The lack of internationally-accepted codes and standards for hydrogen systems in general and fuel cells in particular has a negative reflection on the public's acceptance of hydrogen power solutions. Government officials, policy makers, business leaders, and decision makers would feel more reassured about supporting early-stage hydrogen power projects if general best-practices and consistent safety standards in the design, installation, operation, maintenance, and handling of hydrogen equipment were established. The general public needs to be convinced that hydrogen is similar to conventional fuels in certain aspects and different in other aspects. But overall, hydrogen does not pose a safety issue if properly handled and regulated, just like any other conventional fuel. Codes and standards for hydrogen systems could be made available by the continuous collection of more real-world data and initiation of more trial projects and lab experiments, a process that could be regulated by a professional society or a government initiative (in the US, the Safety, Codes, and Standards sub-program of the Department of Energy Hydrogen and Fuel Cells Program is attempting to take this vital role).

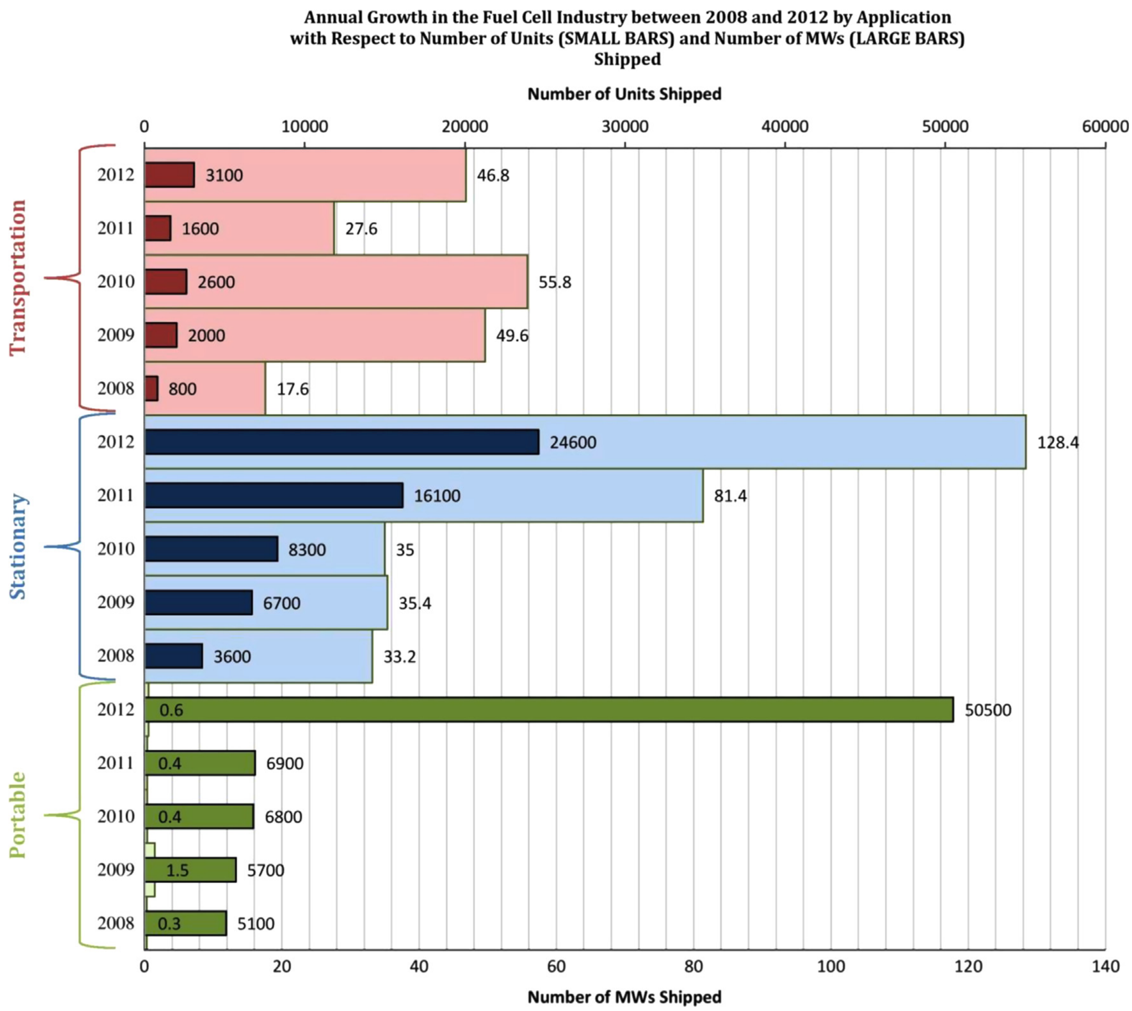


Fig. 7. Annual growth of the fuel cell industry between 2008 and 2012 by application.
Source: Data Sourced from [23].

Table 7 summarizes the main advantages and disadvantages of fuel cells based on the previous discussions. As such, it become clear that fuel cells could play a major role in the portable sector where high energy and power densities and fuel flexibility are sought, in the stationary sector where reduced emissions and high modularity are sought, and in the transportation sector where high efficiencies and quick load-following are sought. These application areas and the fuel cell niche markets within them will be exhaustively covered in the following section.

4. Applications and markets

Fuel cells hold promising potential to become competitive players in a number of markets due to their broad range of applications. And as a result of their high modularity, wide power range, and variation of properties among different types, fuel cells have applications ranging from scooters to large cogeneration power plants as fuel cells can theoretically be used for any energy-demanding application. Efforts towards the commercialization of fuel cells in the portable electronics, stationary power generation, and transportation sectors are well underway. In fact, worldwide shipments of fuel cells increased by 214% between the years 2008 and 2011 with fuel cells becoming an emerging competitor in the back-up power for telecommunication networks market [18], material handling market [19,20], and the airport ground support equipment market [21]. The global fuel cell industry market is expected to reach $19.2 billion by the year 2020 [22] with the United States, Japan, Germany, South Korea, and Canada acting as the flagship countries in the development and commercialization of fuel cells. Worldwide sales in the fuel cell industry are expected to grow 104% between 2010 and 2014 with annual installed power expected to exceed 1.5 GW by 2014 [9]. This was reflected on the employment growth in the fuel cell sector which grew at an average rate of 10.3% annually between the years 2003 and 2010 in the US [9]. Figs. 7–9 show the annual growth of fuel cells by application, region, and fuel cell type, respectively, between the years 2008 and 2012 with respect to both number of units shipped and MWs shipped [23].[1,2]

4.1. Portable applications

Portable applications for fuel cells are mainly focused on two main markets. The first is the market of portable power generators designed for light outdoor personal uses such as camping and climbing, light commercial applications such as portable signage

[1] The 2012 figures are a forecast for the full year.

[2] Portable includes APUs and consumer electronics (toys, gadgets, and educational kits are excluded); stationary applications include small and large stationary prime power, EPS, CHP generation, and CCP generation; transportation refers to vehicles that use fuel cells for the propulsion system.

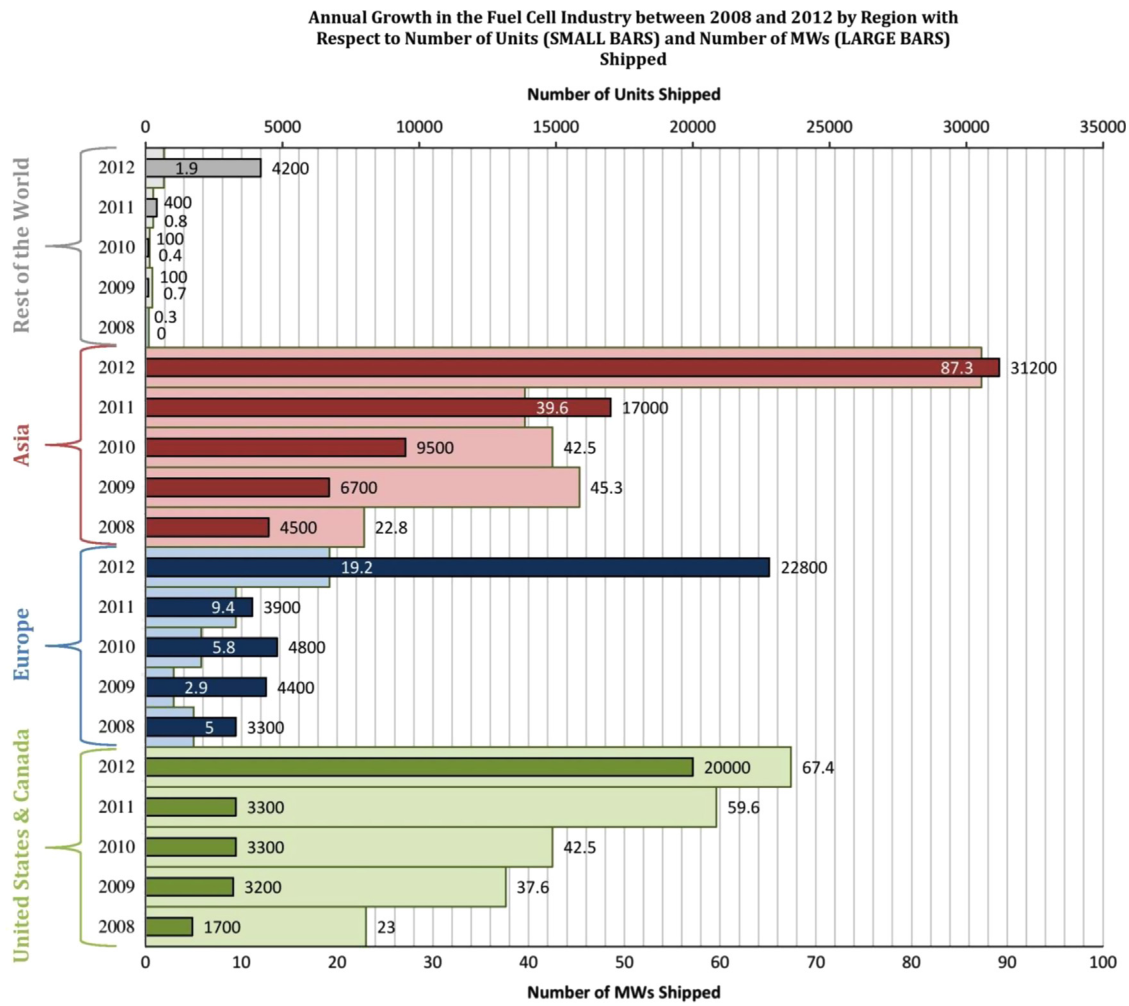


Fig. 8. Annual growth of the fuel cell industry between 2008 and 2012 by region. *Source:* Data Sourced from [23].

and surveillance, and power required for emergency relief efforts. The second is the market of consumer electronic devices such as laptops, cell phones, radios, camcorders, and basically any electronic device that traditionally runs on a battery. Portable fuel cells typically have power ranges between 5 and 500 W, with micro-fuel cells having power outputs less than 5 W and more demanding portable electronics reaching the kW-level. Unlike stationary fuel cells, portable fuel cells could be carried by an individual and used for a variety of applications. The modularity and high energy density of fuel cells (5–10 times higher energy density than a typical rechargeable battery) make them strong potential candidates for future portable personal electronics. Moreover, portable military equipment is another growing application for portable direct methanol fuel cells (DMFCs), reformed methanol fuel cells (RMFCs), and PEMFCs due to their silent operation, high power and energy density, and low weight compared to current battery-based portable equipment [24,25]. In addition to lower weight and higher energy density, the fact that fuel cells do not require recharging from an electricity source makes them more favorable in comparison to batteries in the future portables market. However, their cost and durability are yet to meet set targets. Other rapidly-growing markets in the portable sector include portable battery chargers in addition to miniature demonstration and educational remote control (RC) vehicles, toys, kits, and gadgets by manufacturers such as Horizon [26] and Heliocentris [27]. The vast number of portable equipment being integrated with fuel cells has made roughly half the total number of fuel cell units shipped in 2008 fall into the portable sector category [28], even though on a MW-level, the portable sector accounts for less than 1% of the worldwide fuel cell shipments [29] in the years 2008–2011. However, issues of heat dissipation, emissions dissipation, noise, integrated fuel storage and delivery, shock and vibrations endurance, response time to sharp and repeated demand fluctuations, operation under various operation conditions, tolerance to air impurities, reusability and recyclability of fuel containers, and area exposed to oxygenated air need to be addressed before any serious advances in the portable sector could be made.

4.2. Stationary applications

Fuel cells can play an integral part in the residential, commercial, and industrial stationary power generation sectors. They are utilized for both grid-independent (also known as stand-alone) and gird-assisted power supply. Stationary fuel cell applications include emergency back-up power supply (EPS) (also known as uninterrupted power supply (UPS)), remote-area power supply (RAPS), and distributed power or CHP generation. The stationary fuel cells market accounts for about 70% of the annual fuel cell shipments on a MW-level [29].

4.2.1. Emergency back-up power supply (EPS)

Due to their high energy and power densities, high modularity, longer operation times (2–10 times longer than currently-used

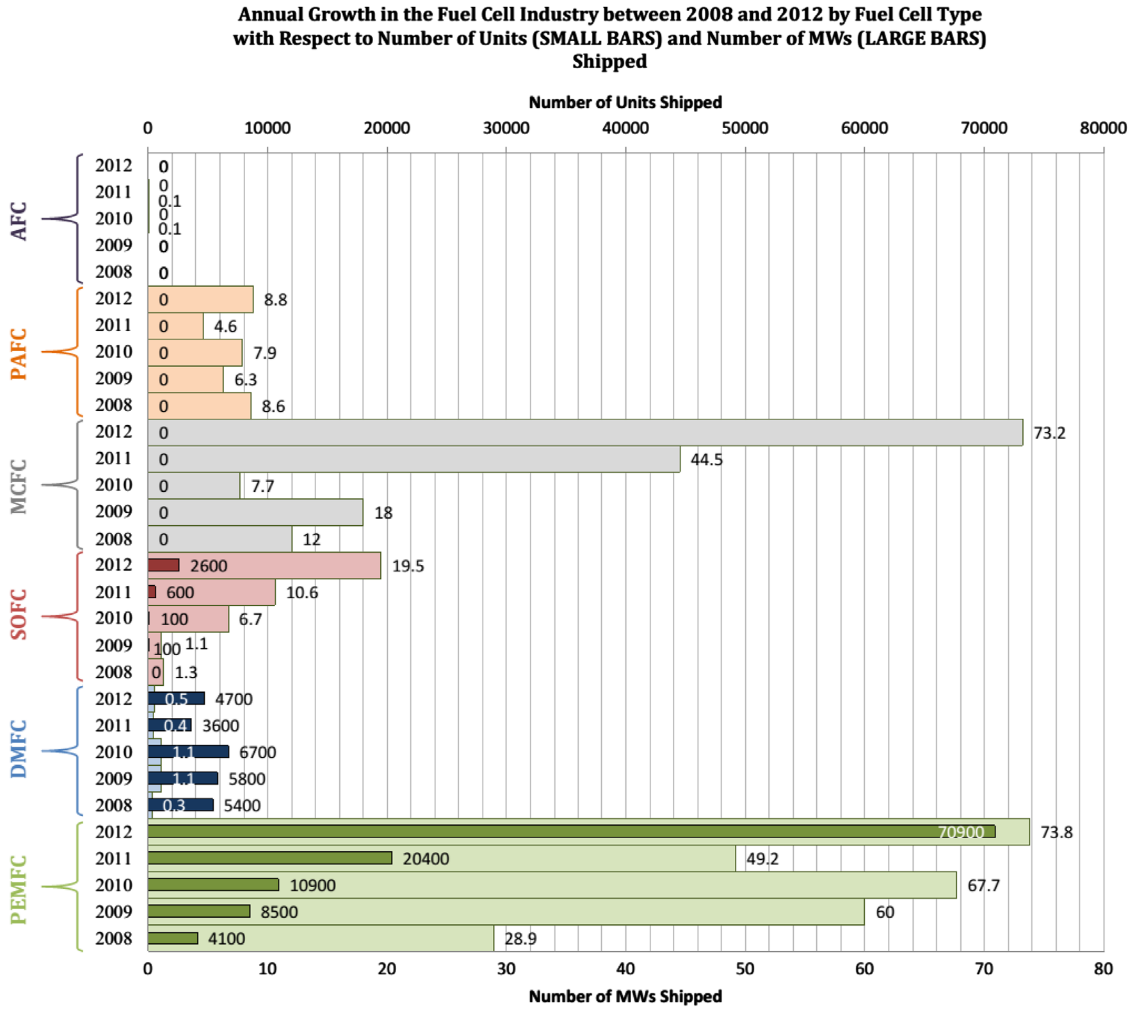


Fig. 9. Annual growth of the fuel cell industry between 2008 and 2012 by fuel cell type.
Source: Data Sourced from [23].

lead-acid batteries), compact size, and ability to operate under harsh ambient conditions, fuel cells are becoming an encouraging alternative for batteries in the EPS market, especially in the telecommunications market, with PEMFCs and DMFCs as the dominantly-chosen fuel cell types [18]. Due to the fact that the EPS market requires high reliability but not necessarily high operational lifetimes, fuel cells found EPS to be one of its most successful markets. Other fuel cell EPS markets include hospitals, data centers, banks, and government agencies. In all these markets, the continuation of a power supply (typically between 2 and 8 kW) is critical, when grid power is unavailable.

4.2.2. Remote-area power supply (RAPS)

In gird-isolated locations, such as islands, deserts, forests, remote technical installations, holiday retreats, and remote research facilities, providing power could be problematic. Such locations fall under the remote-area power supply (RAPS) category. Usually, providing power to rural and urban off-grid locations using RAPS solutions is more economical than extending electric grid power lines. This is especially true for rural areas where the geographical nature of rough terrains (forests, mountains, etc.) makes grid extensions an unrealistic approach. In fact, experts state that extending electric grid lines to rural locations is more expensive when compared to urban locations due to the low load densities in rural areas, high transmission losses for distant areas, and the high cost of the required rural infrastructure that needs to accompany the grid extensions [30]. Off-grid rural areas, especially in developing countries, are a typical example that could significantly benefit from RAPS power generation solutions [31–35]. Off-grid households in urban areas, as well, use various RAPS solutions for their energy needs [36,37]. Currently, RAPS energy solutions are hydrocarbon-based [37], renewable-based [31,34,35,38], or a combination of both [36]. CHP expansion for current RAPS solutions is another option being investigated in order to increase overall system efficiency and add another useful power output, especially for residential urban RAPS locations where the additional increase in capital cost could be tolerated [39]. Similarly, light off-grid industrial and commercial applications, such as technical installations, water pumps, and medical centers use the same RAPS solutions [31,34,38]. Classically, diesel engines have been the energy conversion devices of choice for RAPS. However, diesel engines have high carbon footprints and noisy operation. Fuel cell systems that contain a natural gas or light hydrocarbon reformation component could serve as an alternative for RAPS [37]. However, delivering natural gas or the hydrocarbon through pipelines or other means makes this alternative less appealing for rural and remote locations. Hybrid and integrated energy systems that couple a renewable energy source (such as hydro, biomass, solar, wind, etc.), depending on available natural resources, with a storage mechanism (lead-acid batteries, lithium-ion batteries, hydrogen systems, etc.) provide a more sustainable and autonomous solution for RAPS [31], with solar-PV being the preferred renewable RAPS power generation solution. China and India are leading the

efforts in the utilization of integrated renewable-based systems for the RAPS of rural areas [30]. In fact, by 2030, it is expected that PV-based RAPS systems will amount to 130 GW, with about half of the installed capacity to be utilized in industrial and commercial applications and the other half in the residential sector [40]. A hydrogen system coupled with a renewable energy source is typically composed of a water electrolyzer, hydrogen storage mechanism, and a fuel cell. The utilized hydrogen system would compensate for the intermittency problem most renewable sources suffer from, making the system in its totality both reliable and sustainable. However, PV systems in RAPS applications are typically coupled with batteries for energy storage. Thus, once again, fuel cells are competing with batteries for the same market share. In a comparison conducted by Perrin and Lemaire-Potteau [40] between different types of batteries and hydrogen systems for RAPS applications, it was found that batteries are superior to a hydrogen system with respect to their thermoeconomic performance due to the high cost and low overall efficiency of a hydrogen system. Nevertheless, a RAPS system that uses a hydrogen system for seasonal storage could prove to be favorable. Zoulias and Lymberopoulos [41] found that the complete replacement of batteries with a hydrogen system in a real PV-batteries RAPS system is technically possible, but not yet economically feasible due to the high capital cost for the hydrogen system equipment. Munuswamy et al. [34] concurred the findings of Zoulias and Lymberopoulos [41], stressing that cost reductions in hydrogen systems components are vital for the penetration of renewable-based, hydrogen-facilitated technologies in RAPS. Cost reductions of about 50% for the water electrolyzer, 40% for the hydrogen storage tanks, and a cost of €300/kW for the fuel cell system would make the hydrogen system economically superior to conventional batteries [41]. Khan and Iqbal [36] reached a similar conclusion for a wind-based system that uses a hydrogen system for energy storage. They concluded that in order for the wind–hydrogen system to be advantageous in comparison to the optimal diesel—wind-battery option in the region they conducted their study, the fuel cell cost will have to be reduced by 85% of the current value. With nearly two billion people living without grid electricity, the development of sustainable and reliable RAPS energy solutions becomes a necessity in which fuel cells and hydrogen systems could make a substantial difference if their cost, overall efficiency, and durability issues are resolved.

4.2.3. Distributed power/CHP generation

Fuel cells could serve as the means to make the shift from large centralized power generation to decentralized distributed generation. Due to their static nature, lower emissions, excellent load-following, and high efficiency; fuel cells could be used for residential electric power or CHP distributed generation either on a household basis [42–44] or a larger residential blocks basis [45,46]. In fact, it is estimated that by 2020, fuel cells could penetrate 50% of the world distributed generation market if cost and durability targets are met [32]. This is a market in which Japan is the current leader where thousands of households are already relying on distributed CHP fuel cell systems for their power and heating needs [29]. A residential CHP fuel cell system could range from a few kilowatts to a few megawatts depending on the targeted basis load. A residential CHP fuel cell system will be able to provide electric power, space heating, and domestic water heating requirements. Cooling could also be added to power generation and heating (known as combined cooling, heating, and power (CCHP) systems) if an absorption chiller, thermally-driven heat pump, or an appropriate technique (see Ref. [47]) is integrated with the system to utilize the waste heat of the fuel cell stack in a dual-mode heating/cooling cycle [44,46,48,49]. CHP and CCHP systems could reach overall efficiencies as high as 80% [42,49]; however, further studies to resolve the technical challenges and reduce capital cost in addition to funding for experimental validation remain highly needed. PEMFCs and PAFCs are the best candidates for household basis CHP generation, while high-temperature fuel cells (HTFCs) are more suitable for the larger residential block basis CHP generation. Fuel cell systems used for CHP generation could be designed to either be grid-independent or grid-assisted; however, system complexity and cost increase for grid-independent since the system will have to meet dynamic load fluctuations, which will be more felt for a household basis unit. Oversized fuel cell systems and the integration with battery banks/ultracapacitors are two solutions for this issue; however, both come at a higher cost and system complexity. On the other hand, gird-assisted systems export electricity to the grid during low load demands and import electricity from the grid during peak load demands. For both cases, a thermal storage mechanism is a requirement for an effective CHP system. As for harmful emissions, on a life-cycle assessment basis, MCFCs and PAFCs running on natural gas in CHP cycles emit 78–88% less NO_x emissions, about 60% less particulate matter-10 emissions, and 90–99% less CO emissions in comparison to other combustion-based distributed generation CHP technologies [50]. Aside from residential CHP, combined fuel cell cycles for both energy and chemicals generation in industrial processes [51,52] are being developed. It is worth noting that, regardless of the application for stationary CHP fuel cells, the most challenging technical difficulty remains to increase the lifetime of the fuel cell system to achieve a target of 80,000 h.

4.3. Transportation applications

The transportation industry is one of the main powerhouses in the development of clean energy technologies. This is due to the fact that the transportation industry is responsible for 17% of the global greenhouse gas emissions every year [53]. The industry′s outlook is to invest in technologies that would offer both significant reductions in harmful emissions and better energy conversion efficiencies. Accordingly, the current complete dependence on combustion-based technologies that utilize fossil fuels in heat engines makes the development of environmentally-benign transportation alternatives a necessity rather than an option. This is where fuel cells come into the picture. Fuel cells offer the transportation industry near-zero harmful emissions without having to compromise the efficiency of the vehicle′s propulsion system. In fact, fuel cells have demonstrated efficiencies (from 53% to 59%) that are almost twice the efficiencies of conventional internal combustion engines [54]. When we add advantages such as static operation, fuel flexibility, modularity, and low maintenance requirements; fuel cells become an ideal future alternative for current combustion engines. That is, if durability, cost, hydrogen infrastructure, and technical targets are met on-schedule. This is why using fuel cells in various means of transportation, with a focus on light-duty passenger cars, has been one of the main drivers for fuel cell R&D in the past decade. Japan, for example, has announced an aggressive development plan to deploy two million fuel cell electric vehicles (FCEVs) with one thousand hydrogen refueling stations by 2025 [9]. The share of transportation-related fuel cell shipments worldwide constituted about 35% and 25% of the total fuel cell systems shipped on a number of units basis and a MW-level basis, respectively, in 2010 [29], with PEM as the main fuel cell type chosen. We will classify fuel cell applications that fall under the transportation category into the following markets: auxiliary power units (APUs), light traction vehicles (LTVs), light-duty fuel cell electric vehicles (L-FCEVs), heavy-duty fuel cell electric vehicles (H-FCEVs), aerial propulsion, and marine propulsion. Most of the efforts in the transportation area are focused on APUs and L-FCEVs, as will be observed in the following discussions.

4.3.1. Auxiliary power units (APUs)

An on-board auxiliary power unit (APU) is used for the generation of non-propulsive power in any vehicle. Unlike portable power generators that could be used on-board of recreational vehicles (RVs), boats, etc., an APU is built into the vehicle. The load an APU has to meet could range from less than a kilowatt to loads up to 500 kW on large commercial airplanes. This is why separation of the main propulsion system from the APU is a good strategy to optimize the overall vehicle energy consumption. An APU provides power for air conditioning, refrigerating, entertainment, heating, lighting, communication, and any electrical appliances in any car, boat, ship, locomotive, airplane, truck, bus, submarine, spaceship, military vehicle, or any other vehicle with on-board energy needs. However, leisure yachts, planes, and cars [55]; heavy-duty trucks [56,57]; utility and service vehicles; law enforcement vehicles; and refrigeration vehicles present the most promising markets for APUs due to their high on-board electrical energy demand [58–60]. Leisure and recreational vehicles in particular have extensive on-board APU uses that could mount to more than 38 kW, as seen from Table 8 that lists the APU demands for a typical luxury passenger vehicle in 2000 [61]. With the increased number of on-board comfort features and electrical appliances in the vehicle industry, the demand an APU has to meet is always growing. Fig. 10 shows the structure of a 450 W liquefied petroleum gas-based (LPG-based) PEM fuel cell system with an on-board reformation unit used on a leisure yacht as an APU [55]. Three main APU strategies are currently dominating the market; on-board batteries, on-board hydrocarbon generators, and drawing power from the main propulsion system. Fuel cells as APUs produce significantly less emissions, cause no acoustic pollution, have short start-up times, and have higher efficiencies. To get a feeling of the possible reduction of emissions if fuel cells are used as APUs, a study by Gaines and Hartman [62] concluded that using on-board fuel cell APUs instead of the two most commonly used APUs in heavy-duty trucks in the US – drawing power from the main diesel propulsion engine and separate on-board diesel generators – could decrease particulate matter-10 emissions by up to 65%, NO_x emissions by up to 95%, and CO_2 emissions by more than 60%. Other studies show that truck idling (the practice of keeping the truck's engine on when the truck is not moving for HVAC purposes, electric appliances operation, or keeping the engine ready) accounts for 20–40% of the overall engine running time (about 6 h a day) in heavy-duty trucks that draw power from the engine for APU, during which the energy efficiency is only 3% [59]. Accordingly, a truck on idle mode would consume roughly one gallon of diesel fuel per hour. This represents a great waste of energy and fuel, an extra burden on the engine, a major source of harmful emissions (which led to certain legislations that limit/prohibit truck idling in populated areas), and an impractical engineering practice. Currently, PEMFCs, DMFCs, and SOFCs are the fuel cell types being developed for APU applications with pure hydrogen, natural gas, LPG, gasoline, methanol, and diesel as potential fuels. Other more energy-intensive vehicles, such as commercial airplanes and cargo ships, require APUs with high energy ratings, for which high-temperature fuel cells (SOFCs and MCFCs) become better candidates.

Table 8
APU demands in a luxury passenger vehicle [61].

Accessory	Power demand (W)
Rear wiper	90
Infotronics	100
Windshield pump	100
Heated steering wheel	120
Power sunroof	200
Truck closer	200
Windshield wipers	300
Air pump	400
Power door locks	400
Engine coolant pump	500
Antilock braking system (ABS) pump	600
Lights	600
Power windows	700
Electric fan	800
Rear defrost	1000
Power seats	1600
Steer by wire	1800
Brake by wire	2000
Heated front seats	2000
Heated windshield	2500
Catalyst heating	3000
Electromechanical valve control	3200
Air conditioning	4000
Active suspension	12,000

4.3.2. Light traction vehicles (LTVs)

Light traction vehicles (LTVs) include scooters, personal wheelchairs, electric-assisted bicycles, airport tugs, motorbikes, golf carts, etc. in addition to material handling vehicles and equipment. Material handling vehicles and equipment include forklifts, tow trucks, pallet trucks, etc. and fall under the LTVs category. Forklifts have been the most successful demonstration of fuel cells in the transportation sector, and one of the most successful demonstrations for fuel cells overall. Forklifts and other material handling vehicles and equipment are exhaustively used in the warehousing and distribution industry, with nearly 2.5 million forklifts in-operation in North America [63]. Most forklifts use rechargeable lead-acid batteries (usually with regenerative braking energy recovery) or combustion engines (either compression ignition engines running on diesel or spark ignition engines running on gasoline, LPG, compressed natural gas, or propane). However, since fuel cells require only 2–5 min for refueling from a fueling station in contrast to recharging or changing batteries which takes 15–30 min (which increases operational efficiency), have longer operation cycles in contrast to battery cycles which usually last less than 8 h (again, increasing operational efficiency), are less sensitive to the ambient temperature (especially in refrigerated warehouses) in contrast to batteries, do not self-degrade with charge and discharge cycles in contrast to batteries, require much less space for refueling stations in contrast to battery charging and changing space, have significantly less harmful emissions compared to combustion-based engines, can operate indoor or outdoor in

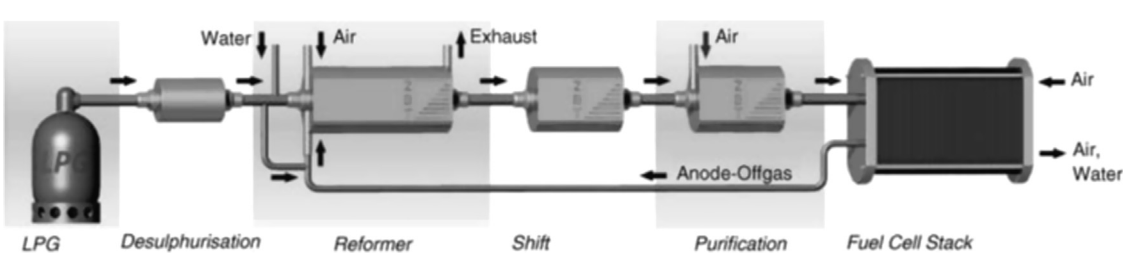


Fig. 10. 450 W PEM fuel cell system with on-board reformation for APU on a Leisure Yacht [55].

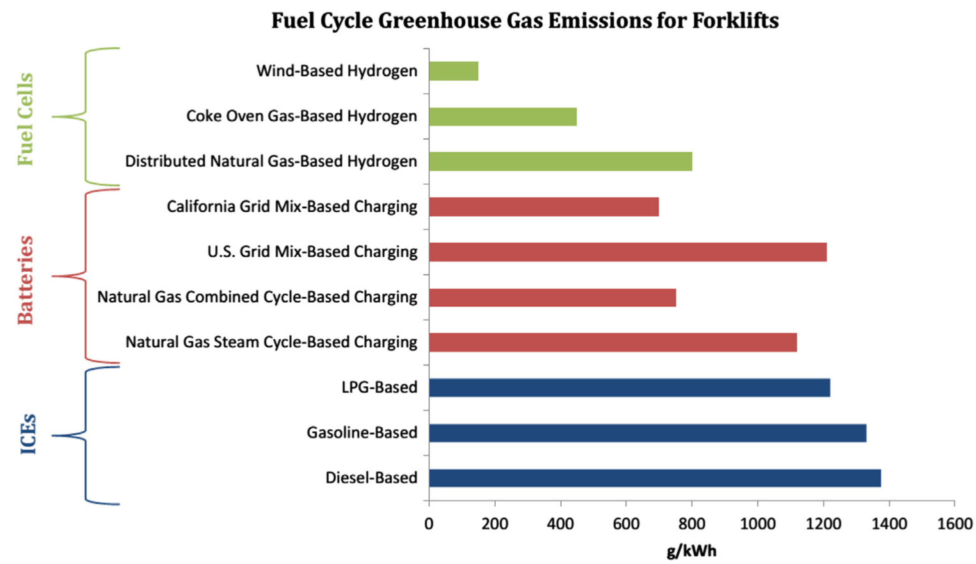


Fig. 11. Fuel cycle GHG emissions for ICE-, battery-, and fuel cell-powered forklifts.
Source: Data Estimated from [9].

contrast to many combustion-based forklifts that cannot run indoors, have high efficiencies, have excellent load-following dynamics, and require low maintenance; they have a huge potential to gradually replace conventional forklifts. It is important to notice that liquid hydrogen/fuel feeding systems that use a fueling station are much more practical than on-board hydrogen reformation or generation systems that tend to be bulky and could significantly slow down the response time. Fig. 11 shows the fuel cycle greenhouse gas (GHG) emissions of forklifts that use diesel engines, gasoline engines, LPG engines, batteries with charging from the average US electric grid mix, batteries with charging from the average California electric grid mix, batteries with charging from a simple natural gas steam cycle, batteries with charging from a combined natural gas cycle, fuel cells with hydrogen from steam reforming of methane (the main component in natural gas), fuel cells with hydrogen from coke oven gas (COG), and fuel cells with hydrogen from wind energy. The fuel cycle GHG emissions includes in the calculations the upstream emissions that accompanied converting primary energy sources into the usable forms in the forklifts, the point of use emissions (which is applicable only to combustion engine-based forklifts), and emissions from hydrogen compression for fuel cells [8]. Around 1300 fuel cell-powered forklifts are operative in the US market today [64]. Fuel cell forklifts are typically operated on 5–20 kW PEMFCs, with few models running on DMFCs, coupled with ultracapacitors for instantaneous power response support. Plug Power remains as the biggest player in the fuel cell forklift market since the company is solely focused on the material handling market. Fuel cell-powered scooters [65,66] and fuel cell-powered electric-assisted bicycles [67] are also being developed and expected to have a good share of the future fuel cell market since they help avoid traffic congestions, are ideal for short- and medium-distances trips, are environmentally-benign, and do not consume expensive hydrocarbon fuels. It is important to note that motorcycles, scooters, and electric-assisted bicycles are differentiated in descending order based on the power requirement, total weight, available speed, and travel distance. Scooters have power requirements between 4 and 6 kW with travel distances up to 200 km, while electric-assisted bicycles require less than 1 kW of power with a travel distance less than 1 km. Electric-assisted bicycles use a combination of human pedaling and electric motors that run on batteries. For the same reasons listed in our discussion on forklifts (emissions, charging time, operation duration, etc.), fuel cell-powered scooters and electric-assisted bicycles are favorable to combustion- and battery-based ones. Other fuel cell-powered LTVs such as light carts [68] and personal wheelchairs [69] have also been demonstrated.

4.3.3. L-FCEVs

Light-duty fuel cell electric vehicles (L-FCEVs) utilize a fuel cell for the propulsion system. When compared to the current internal combustion engine-based vehicles, L-FCEVs provide quitter operation (due to the static nature of fuel cells), more efficient energy use (nearly twice the efficiency of internal combustion systems, as mentioned earlier, and the potential for about 30% higher well-to-wheel efficiency [70]), significantly less point-of-use GHG emissions (and the potential for near-zero lifecycle GHG emissions if renewables are used for the production of hydrogen), and more vehicle design and packaging flexibility. When compared to light-duty battery electric vehicles (L-BEVs), L-FCEVs provide a longer range, shorter refueling time (less than 2 min), better tolerance of cold weather, and lighter weight. However, lifecycle cost and stack durability limitations are the reasons L-FCEVs have not become commercially-available yet. Other technical barriers that need to be resolved are related to total system weight and size; air compression systems; start-up in very cold weather and under frozen conditions; heat dissipation; catalyst tolerance to voltage cycling; stack endurance of frequent start-stop cycles; bipolar plates weight; on-board hydrogen storage; membrane humidification; and hydrogen safety standards. Due to the inherent advantages (related to dynamics response, operation temperature, system size, etc.) PEMFCs hold over other fuel cell types, hydrogen PEMFCs are the most used fuel cells in L-FCEVs research, development, and demonstration efforts. General Motors, Toyota, Mazda, Daimler AG, Volvo, Volkswagen, Honda, Hyundai, Nissan, and other major car manufacturers are steadily progressing for the near-term commercialization of L-FCEVs that utilize a fuel cell for the main propulsion system through an electric motor connected to the fuel cell system. February 26, 2013 witnessed a major milestone in the history of the fuel cell industry as Hyundai announced the completion of its first assembly line mass-produced L-FCEV, the ix35 [71]. The Korean automobile manufacturer will deliver its first 17 L-FCEVs to customers in Denmark and Sweden in a few months. The company aims to have 1000 of its ix35′s running on the streets of Europe by 2015 with a cost of $50,000 per car. The vehicle has a range of nearly 600 km and a

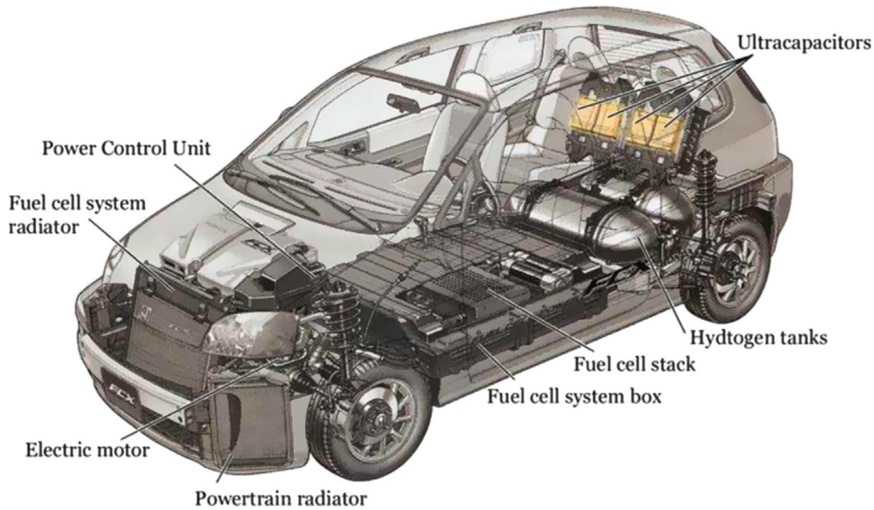


Fig. 12. Conceptual design of a future L-FCEV based on the Honda 2005 FCX model [72].

top speed of 160 kmph using its hydrogen/air fuel cell system, that could run at temperatures as low as −25 °C, coupled with a Li-ion battery for regenerative braking energy recovery. The main typical components of a L-FCEV include fuel cell stacks; cooling systems for the stack, motor, and transmission; high-pressure hydrogen storage tanks (or any compact, light, and energy-dense storage mechanism); electric motor; main power control unit; high-voltage batteries and/or ultracapacitors for regenerative braking energy recovery (which could increase the driving range by 5–20% [70]) and response to transient power surges; air and hydrogen supply systems; power conditioning electronics; and other auxiliary BoP components. Fig. 12 shows the conceptual design of a typical future L-FCEV [72].

The main competition for L-FCEVs comes, as one would expect, from L-BEVs, with nickel metal-hydride (NiMH) batteries currently dominating the L-BEVs market and lithium-ion (Li-ion) batteries steadily progressing to be the future choice in L-BEVs [73]. Both L-FCEVs and L-BEVs have advantages and disadvantages that are highly dependent on the primary energy source (fossil, renewable, biomass, etc.), energy conversion chain (e.g., hydrogen production, transport, and storage mechanisms), and design requirements (maximum speed, driving range, passenger capacity, etc.). The results of a study conducted by Campanari et al. [74] to compare the energy and environmental characteristics of L-BEVs and L-FCEVs imply that using light-duty hybrid electric vehicles (L-HEVs) that utilize both batteries and fuel cells in an attempt to combine their advantages might be an interim solution until one of the technologies (both PEMFCs and Li-ion batteries are still immature and going through rapid technological advances) shows obvious superiority over the other. For example, the power demand could be distributed between the fuel cell and the battery where one meets the bulk average power demand while the other meets the transient acceleration fluctuations, which would improve the fuel cell′s durability due to avoidance of repeated voltage cycling and help avoid the design of an oversized fuel cell system. A comprehensive study that compared state-of-the-art advanced Li-ion, Ni-MH, and deep discharge lead-acid batteries with PEM fuel cells using computer simulations by Thomas [75] concluded that L-FCEVs are superior to L-BEVs for any driving range greater than 160 km with respect to vehicle′s mass, storage volume, incremental vehicle cost, incremental lifecycle costs, GHG emissions, refueling time, and well-to-wheel energy efficiency when natural gas or biomass are the primary energy source. Fig. 13 presents modeling estimates for the amount of greenhouse gas emissions and the level of petroleum use for future light-duty mid-size passenger cars that utilize hydrogen fuel cells, batteries, diesel fuel, gasoline fuel, cellulosic ethanol, corn ethanol, and natural gas for the propulsion system [76]. For each type there are some technological variations, as seen from the figure. For example, the source of the electricity used to charge the batteries (grid electricity or renewable-based electricity) for a future mid-size L-BEV makes a noticeable impact on the GHG emissions and level of petroleum use. The modeling estimates have been carried using a projected technological state to 2035–2045 that does not include life-cycle effects of vehicle manufacturing and infrastructure (for a full record of the assumptions and references used for the models and estimates refer to [76]). In the figure, the renewables referred to are carbon-free technologies such as solar, wind, and ocean energy. Cars that use batteries, hydrogen fuel cells, cellulosic ethanol, and corn ethanol have much lower GHG emissions when compared to other technologies. While for the petroleum use, batteries, hydrogen fuel cells, and natural gas have the lowest levels. All renewable-based technologies show superiority with respect to both GHG emissions and petroleum use when compared to other technological variations within each type. However, renewable-based L-FCEVs remain dependent on simultaneous technological advances in hydrogen production, storage, and delivery; making natural gas-based and biomass-based L-FCEVs a more forthcoming and practical light-duty transportation alternative for the short-term future.

The hydrogen fuel required to run a L-FCEV is usually generated off-board and distributed in dedicated fueling stations where hydrogen is then dispensed to the hydrogen storage system on-board of the vehicle. On-board hydrogen storage is one of the biggest challenges and most active research areas for the commercialization of FCEVs. Using compressed hydrogen, liquid hydrogen, metal hydrides, chemical hydrides, and other novel storage technologies are all being evaluated. Unlike for stationary applications, the constraints for the hydrogen storage system in transportation applications are more demanding and inflexible. In addition to the low cost, high efficiency, and low parasitic load (e.g. for compression, cooling, or discharging) constraints; gravimetric energy density (the leading issue with metal-hydrides), volumetric energy density (the leading issue with compressed gas), collision safety requirements, fitting into the vehicle′s space and shape, and system complexity are additional constraints for a hydrogen storage system on-board of most means of transportation. In fact, a recent study by Ahluwalia et al. [77] shows that none of the currently-available hydrogen storage mechanisms meet the long-term targeted characteristics for a future L-FCEV.

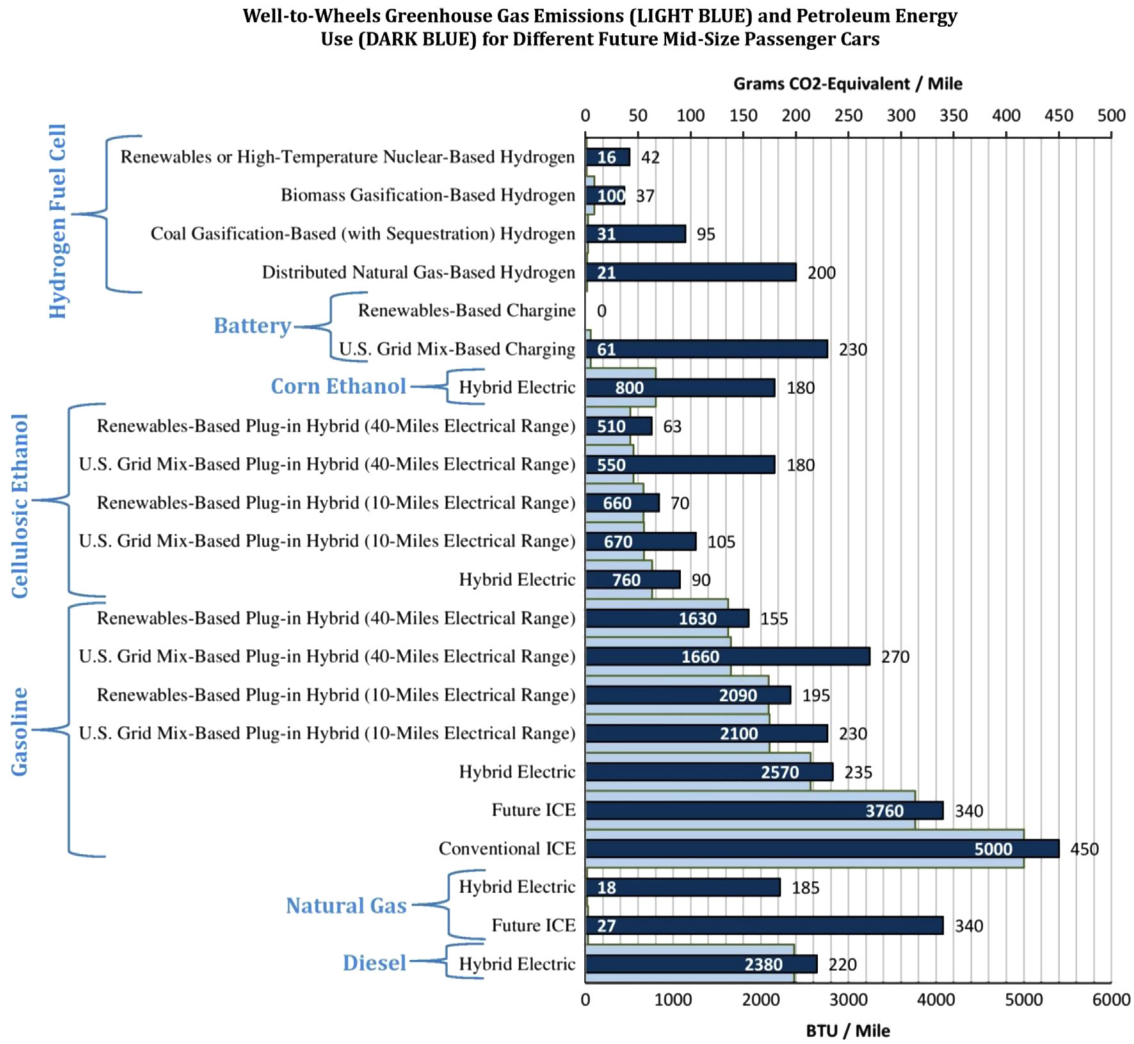


Fig. 13. Well-to-wheel greenhouse gas emissions and petroleum energy use estimates for future mid-size passenger cars using different propulsion technologies.
Source: Data Sourced from [76].

However, the study concludes that cryo-compressed hydrogen storage, ammonia borane chemical storage, and alane metal hydrides hold the most potential for meeting future storage targets; given that certain technical issues are resolved. It is worth noting that using on-board reformation (or any other hydrogen production method) for hydrogen generation is still impractical due to size, weight, start-up time, and safety limitations. Nevertheless, with advances in reformation and hydrogen production technologies, on-board generation could become feasible.

4.3.4. H-FCEVs

Heavy-duty fuel cell electric vehicles (H-FCEVs) include buses, heavy-duty trucks, locomotives, vans, utility trucks, service fleets, etc. that utilize a fuel cell for the electric propulsion system. With more than 30 fuel cell buses currently deployed in Western Europe [78] and another 25 in the United States [79] in 2012; fuel cell electric buses (FCEBs) are becoming one of the best public demonstration tools and R&D data sources in the fuel cell transportation industry. And with public transportation becoming more desirable for urban communities in order to help reduce harmful emissions and avoid traffic congestions from the use of personal cars; buses are one of the most appealing applications for fuel cell technology in order to progress towards clean public transportation. FCEBs provide very low emissions (zero point-of-use emissions for buses that only use hydrogen fuel cells and batteries) when compared to conventional diesel-based buses, silent operation, and higher efficiency compared to other combustion-based busses, making them favorable to the public and the policy makers. While when compared to other fuel cell-powered vehicles, buses provide more flexible design and packaging, less complex hydrogen infrastructure requirements since bus routes are usually fixed, and more flexible weight and size constraints for the hydrogen storage system. This is why numerous programs funded by governments and the private sector were found with the aim of deploying FCEBs in the US, Canada, Western Europe, Japan, China, Australia, and South America. Key examples include the Sustainable Transport Energy Programme (STEP) initiative in Australia [80], the Clean Urban Transport for Europe (CUTE) and HyFLEET:CUTE (which is the world's largest FCEBs demonstration program with 33 FCEBs deployed) projects in Europe [81], the Hydrogen Fuel Cell Demonstration Project in Canada [82], the Urban-Route Buses Trial Project in China [83], the Brazilian Fuel Cell Bus Project in Brazil [84], and the Zero Emission Bay Area (ZEBA) demonstration in California, United States [85]. Fig. 14 shows the main components in a typical FCEB [86]. It is clear from the figure that the design utilizes the space flexibility on the roof, front, and back of the bus. Thus, the bus floor could be made lower compared to other conventional buses. The main components are very similar to those previously described for the

L-FCEV, with PEMFCs and PAFCs being the most commonly-used types for the stack and high-voltage batteries used for regenerative braking energy recovery and a better dynamic response. However, the immaturity of fuel cell technologies and the lack of mass production and manufacturing are making FCEBs economically-uncompetitive with conventional buses and other competing novel technologies. This is more evident for FCEBs than L-FCEVs due to the higher durability and reliability requirements in FCEBs. Nevertheless, progress in the durability and cost of fuel cells designed for FCEBs is underway due to the increasing number of demonstration programs and the efforts by both fuel cell and bus developers such as Ballard, Hydrogenics, and Daimler AG.

Even though in the transportation sector, L-FCEVs, FCEBs, and fuel cell-based APUs are dominating the market, several impressive demonstrations and milestones have recently been achieved for H-FCEVs. Vision has announced the commercialization of what it claims to be the world's first hydrogen fuel cell-based heavy-duty class-8 truck. The 8.4 m long by 2.9 m high truck runs on a hybrid hydrogen fuel cell/Li-ion battery drive system capable of running at temperatures as low as −26 °C and as high as 43 °C while providing peak power of about 400 kW and a top speed of about 105 kmph at total vehicle weight of more than 36,000 kg. The fuel cell system (developed by Hydrogenics) has an output of 65 kW, a range of more than 320 km, and refueling time between 4 and 7 min. A purchase order for 100 of Vision's trucks has been signed by the Total Transportation Services (TTS) with a total worth of $27 million [87]. Similarly, Heliocentris is developing a hybrid waste disposal heavy-duty truck that uses a hybrid diesel engine/fuel cell system in Germany. The diesel engine will be used for propulsion while the fuel cell will be used for waste collection, management, and disposal. While for rail vehicles, Guo et al. [88] designed and simulated the performance of a proposed power system for a hybrid switcher locomotive that uses a SOFC power plant, lead-acid batteries, and ultracapacitors for the locomotive's propulsion. The results of the study show that using the proposed control strategy for regulating the load sharing between the three sources would meet the locomotive's required power demand with high efficiency. On the other hand, Miller et al. [89] found that using only a fuel cell for the power plant of a 1.2 MW yard switcher locomotive is actually more effective than using a hybrid fuel cell design coupled with auxiliary storage devices. This is because for a switcher locomotive, complex transient power requirements are not an issue since adhesion between the wheels and the rails is the limiting factor for tractive power, and not the peak power available. Additionally, potential for recovery of regenerative braking energy is low and the added complexity, volume, and weight of a hybrid design could be problematic.

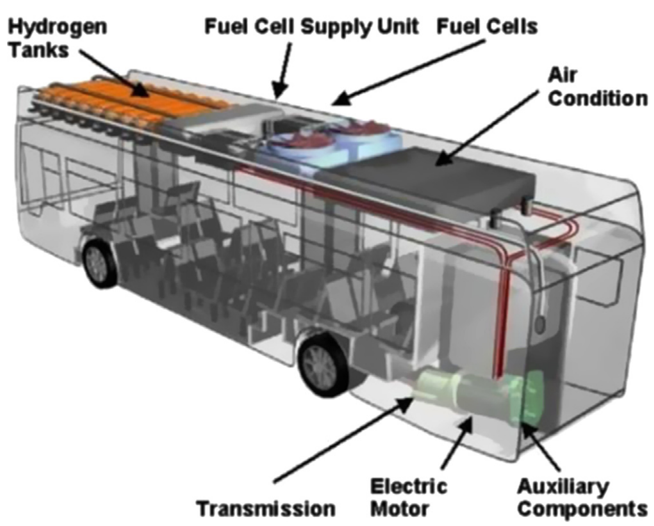


Fig. 14. Main components in a typical FCEB based on the Mercedes-Benz Citaro Fuel Cell EcoBus [86].

4.3.5. Aerial propulsion

Other applications for fuel cells include the space and aviation industries with small unmanned aerial vehicles (UAVs) being the main focus for fuel cells in the aerial propulsion sector. UAVs are mainly used for surveying, surveillance, and reconnaissance purposes due to their stealth nature and lack of risk to human life. And with the ever-increasing interest in UAVs by military authorities and commercial parties, the development of more durable and reliable propulsion systems is a necessity. Fuel cells (mostly PEMFCs with few SOFCs) are clearly becoming the ideal candidates for powering future UAVs. The stealth nature of UAVs is facilitated by fuel cells' static operation and low heat dissipation, two advantages over UAVs with internal combustion engines. And even though batteries share those two advantages with fuel cells, the low energy density and large weight of batteries make fuel cell UAVs superior to UAVs with batteries. The lighter weight and higher energy density of fuel cells allow for greater mission range and endurance (up to 24 h [64]) as compared to an average of one hour for battery UAVs. Additionally, the modularity of fuel cells

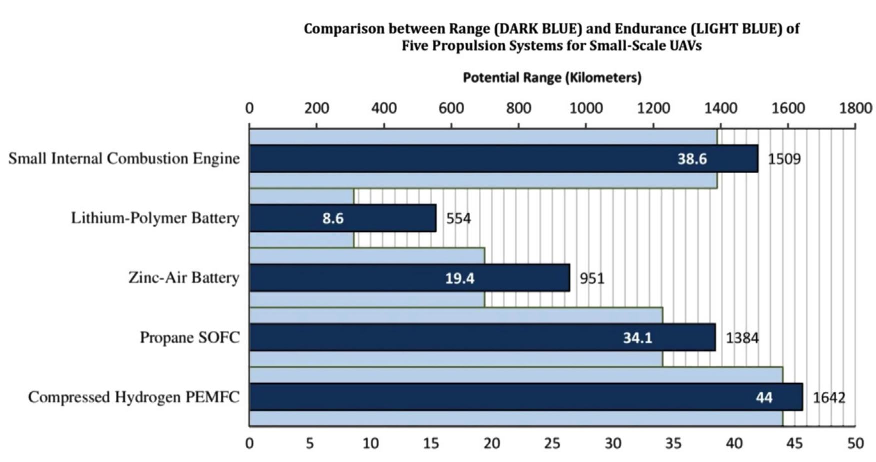


Fig. 15. Comparison between different proposed UAV small-scale propulsion systems.
Source: Data Sourced from [90].

makes them promising to use for small-scale applications such as UAVs, contrary to combustion engines that suffer from low efficiencies when designed for small-scale applications. Thus, about 20 UAVs with fuel cells have been demonstrated so far [64]. A comparison conducted by Bradley et al. [90] between five different potential small-scale UAV propulsion systems concluded that a PEMFC system with compressed gaseous hydrogen has the highest potential for both range and endurance. The other four systems were a propane-based SOFC, a lithium polymer battery, a zinc air battery, and a small internal combustion engine. The results of the comparison are summarized in Fig. 15.

Kim et al. [91] designed, built, and tested a UAV with a hybrid fuel cell/battery propulsion system with on-board hydrogen production using sodium borohydride. They used the fuel cell to meet the steady-state power demand during cruising while both the battery and the fuel cell provided the power required for the more power-demanding take-offs and maneuvers. They concluded that using fuel cell systems in UAVs is more efficient than battery- and combustion-based UAVs for long endurance flights. Another innovative and highly-efficient concept was NASA's Helios UAV that used a hybrid propulsion system consisting of photovoltaic cells, a regenerative fuel cell, and backup batteries for achievement of both high altitudes and long flights. The regenerative fuel cell functions as an electrolyzer that generates hydrogen during the day using power from the photovoltaic cells and then functions as a fuel cell that uses this hydrogen for flight during the night. Other demonstrations include EnergyOr Technologies demonstration of a long endurance flight for more than 10 h with its fuel cell-powered UAV using the company's own fuel cell system [29]. On the other hand, the market of manned military and commercial air vehicles is still impractical for fuel cells due to the market's high energy density, power density, durability, and reliability requirements. Nonetheless, in 2008 Boeing announced the successful testing of a small airplane using a hybrid hydrogen PEMFC system, developed by Intelligent Energy, coupled with an engine and Li-ion batteries [92]. A few other manned fuel cell-based airplanes have also been demonstrated afterwards, of which, a demonstration by DLR in Germany used a system that relied solely on a hydrogen fuel cell with a range of 750 km, an endurance of 5 h, and a fuel cell efficiency of 52% [93]. In Japan, a team of researchers successfully designed, simulated, and tested a fuel cell-powered high-altitude balloon [94]. Moreover, the space industry has been one of the first to adopt fuel cells. NASA used AFCs and PEMFCs for its manned space programs during the 1960s. However, during the past 10 years, interest in fuel cells for space applications has been revived [95–97]. Fuel cells are attractive for space applications due to their many advantaged compared to other power generation technologies. However, the fact that water is a byproduct of the electrochemical reactions within a fuel cell makes it even more attractive for space applications where air, water, and food supplies are of the utmost importance.

4.3.6. *Marine propulsion*

Even though the most common use for fuel cells in the marine industry is as APUs on-board of boats and yachts, as previously mentioned, promising future marine propulsion markets for fuel cells exist in submarines, ferries, underwater vehicles, boats, yachts, and even cargo ships. Fuel cells provide their regular benefits for ships and ferries, such as low emissions, high efficiency, and static operation. However, issues related to reliability, lifetime, shock resistance, and tolerance to the salt content of sea air are yet to be resolved. Currently, PEMFCs, SOFCs, and MCFCs hold the most potential for the marine fuel cell market. In 2003, the first yacht with a certified hybrid PEMFCs/lead-gel batteries system for both propulsion and APU was successfully demonstrated in Germany [98]. While for commercial ships, in 2008, the world's first commercial passenger ship running on a hybrid PEMFCs/lead-gel battery system was put into service in Germany. The ship has a capacity of 100 passengers and offers twice the efficiency of a conventional diesel-based ship [99]. Another innovative and self-sufficient hydrogen fuel cell boat was developed in Austria in 2009 [100]. The boat's propulsion system consists of photovoltaic panels, an electrolyzer, a high-pressure hydrogen storage system, and a fuel cell. The system uses solar energy to decompose water in the electrolyzer into hydrogen and oxygen. The hydrogen is then fed to the fuel cell system for propelling the boat. According to the developers, the boat has a range of 80 km, which is twice the range of a conventional battery-based boat. Furthermore, in 2011, the world's first hydrogen fuel cell-propelled ferry has been in daily operation in Germany [29]. Alkaner and Zhou [101] concluded that using conventional marine fuels reformation on-board of ships for hydrogen generation is the solution to overcome the low volumetric density of hydrogen and to make fuel cells a practical propulsion alternative in commercial ships. The researchers also concluded based on a life cycle assessment (including manufacturing, fuel production, operation, and decommissioning) that using MCFCs with on-board reformation holds no significant advantage over conventional diesel engines with respect to neither energy nor environment. This is mainly due to the immaturity of MCFC technology, the low durability of MCFC stacks (about 5 years), and the use of energy-intensive materials and manufacturing processes due to the lack of commercial production. Leo et al. [102] conducted an extensive exergy analysis of two proposed fuel configurations for power generation in marine applications. The first configuration used a PEMFC coupled with a liquid methanol reformation stage. The second configuration used a DMFC. The results of the analysis showed that both systems had similar exergy efficiencies (even though more exergy was lost in the DMFC configuration) and for more conclusive results, a thermoeconomic analysis should be conducted in order to take the economic factor into account. Submarines that use oxygen/hydrogen fuel cells for propulsion and auxiliary load requirements have also been successfully deployed. A series of PEMFC-based hybrid submarines

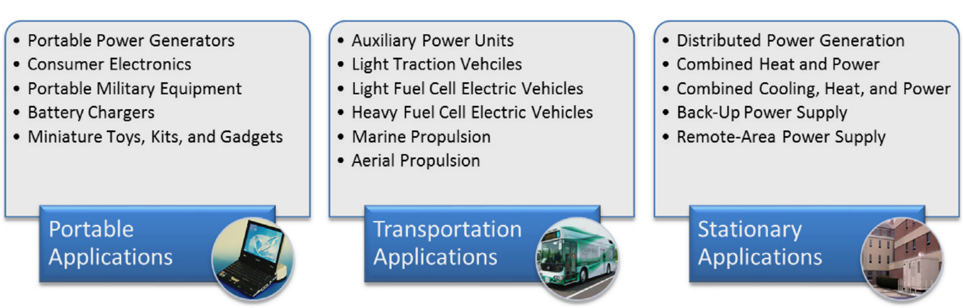


Fig. 16. Summary of fuel cell applications.

Table 9
Major fuel cell system solutions development companies.

Country	#	Company	FC type(s)	Market(s)
United States	1	Acumentrics	SOFCs	• RAPS • Portable military equipment • Industrial and residential distributed CHP generation • Commercial distributed power generation • EPS
	2	Altergy	PEMFCs	• EPS
	3	Bloom Energy	SOFCs	• Commercial distributed power generation • EPS
	4	Boeing	PEMFCs	• Aerial propulsion • APUs
	5	ClearEdge Power[a]	PEMFCs PAFCs	• Residential and commercial distributed power generation • Residential and commercial distributed CHP generation • EPS • APUs • L-FCEVs • H-FCEVs
	6	Delphi	SOFCs	• APUs
	7	EnerFuel	PEMFCs	• Residential and commercial distributed power generation • Residential and commercial distributed CHP generation • EPS • APUs
	8	First Element	PEMFCs	• EPS • Industrial and commercial distributed power generation • RAPS
	9	Ford	PEMFCs	• L-FCEVs
	10	FueCell Energy[b]	MCFCs SOFCs	• Commercial and industrial distributed power generation • Commercial and industrial distributed CHP generation
	11	General Motors	PEMFCs	• L-FCEVs • H-FCEVs
	12	Infinity	PEMFCs	• APUs
	13	Infintium	PEMFCs	• Material handling
	14	Microcell	PEMFCs	• EPS • Portable power generators • Commercial distributed CHP generation • Commercial distributed CCHP generation
	15	Motorola	DMFCs	• Consumer electronics • EPS
	16	MTI Micro	DMFCs	• Consumer electronics • Battery chargers
	17	Neah Power	DMFCs	• Consumer electronics • Portable power generators • Portable military equipment
	18	Nuvera	PEMFCs	• Material handling • APUs • L-FCEVs • Residential distributed power generation
	19	Oorja	DMFCs	• Material handling
	20	Plug Power	PEMFCs	• Material handling

Table 9 (*continued*)

Country	#	Company	FC type(s)	Market(s)
	21	Protonex	PEMFCs SOFCs	• Portable military equipment • UAVs • Battery chargers • APUs • Portable power generators • EPS • RAPS
	22	ReliOn	PEMFCs	• EPS • RAPS
	23	Ultra Electronics AMI	SOFCs	• Consumer electronics • APUs • Battery chargers • Portable military equipment • Portable power generators
	24	UltraCell	RMFCs	• Consumer electronics • Portable power generators • Portable military equipment
	25	Vision	PEMFCs	• H-FCEVs
Japan	1	Canon	PEMFCs	• Consumer electronics
	2	Fuji Electric	PAFCs PEMFCs	• Industrial and commercial distributed power generation • Industrial and commercial CHP generation
	3	Hitachi	SOFCs DMFCs	• Residential distributed CHP generation • Consumer electronics • Portable power generators
	4	Honda	PEMFCs	• LTVs • Residential distributed CHP generation • L-FCEVs
	5	IHI	PEMFCs MCFCs	• Residential and commercial distributed power generation • APUs
	6	Mitsubishi	PEMFCs SOFCs	• L-FCEVs • H-FCEVs • Residential and commercial distributed power generation • Residential and commercial distributed CHP generation • Marine propulsion
	7	NEC	DMFCs	• Consumer electronics
	8	Nissan	PEMFCs DMFCs	• L-FCEVs
	9	Panasonic[c]	PEMFCs DMFCs	• Residential distributed CHP generation • Portable power generators • Consumer electronics
	10	Sony	Microbial FCs DMFCs	• Consumer electronics • Battery chargers
	11	Suzuki	PEMFCs	• LTVs • L-FCEVs
	12	Toshiba	DMFCs PEMFCs PAFCs	• Consumer electronics • Battery chargers • Residential distributed CHP generation • EPS
	13	Toyota	PEMFCs SOFCs	• H-FCEVs • L-FCEVs • Material Handling • Residential distributed CHP generation
	14	Yamaha	DMFCs	• LTVs

Table 9 (*continued*)

Country	#	Company	FC type(s)	Market(s)
Germany	1	Baxi Innotech	PEMFCs	• Residential distributed CHP generation
	2	BMW	PEMFCs	• APUs • L-FCEVs
	3	Daimler[d]	PEMFCs	• L-FCEVs • H-FCEVs
	4	FutureE	PEMFCs	• EPS • RAPS • Distributed power generation
	5	Heliocentris	PEMFCs	• Toys and educational kits • RAPS • EPS
	6	Proton Motor	PEMFCs	• H-FCEVs • Material handling • EPS • Marine propulsion
	7	Schunk	PEMFCs	• Battery chargers • General-purpose stacks and systems
	8	SFC Energy	DMFCs	• Battery chargers • RAPS • EPS • Portable power generators • Portable military equipment
	9	Siemens	DMFCs PEMFCs SOFCs	• Consumer electronics • Marine propulsion • Industrial distributed CHP generation
	10	Volkswagen[e]	PEMFCs	• L-FCEVs • H-FCEVs • APUs
Canada	1	AFCC	PEMFCs	• L-FCEVs • H-FCEVs
	2	Ballard[f]	PEMFCs DMFCs	• EPS • Commercial distributed CHP generation • RAPS • Material handling • H-FCEVs
	3	DDI Energy	SOFCs	• RAPS • EPS • Residential and commercial distributed power generation • Residential and commercial distributed CHP generation • APUs
	4	Hydrogenics	PEMFCs	• RAPS • Material Handling • H-FCEVs • Marine propulsion • Aerial propulsion • EPS • L-FCEVs
	5	New Flyer	PEMFCs	• H-FCEVs
	6	Palcan	PEMFCs	• EPS • RAPS • Portable power generators
United Kingdom	1	AFC Energy	AFCs	• Industrial distributed power generation
	2	Ceres Power	SOFCs	• Residential distributed CHP generation • APUs • Portable power generators • EPS

Table 9 (*continued*)

Country	#	Company	FC type(s)	Market(s)
	3	Intelligent Energy	PEMFCs	• L-FCEVs • LTVs • EPS • Residential and commercial distributed CHP generation • Consumer electronics
	4	Morgan	PEMFCs	• L-FCEVs
	5	Riversimple	PEMFCs	• L-FCEVs
South Korea	1	Hyundai	PEMFCs	• H-FCEVs • L-FCEVs
	2	Kia	PEMFCs	• L-FCEVs
	3	LG[g]	DMFCs SOFCs	• Consumer electronics • Industrial and commercial distributed CHP generation
	4	Samsung	DMFCs PEMFCs SOFCs	• Consumer electronics • Portable power generators • Portable military equipment • Distributed power generation
Sweden	1	Cellkraft	PEMFCs	• RAPS • EPS • Portable military equipment
	2	myFC	PEMFCs SOFCs	• Consumer electronics • Battery chargers
	3	Powercell	PEMFCs	• APUs • EPS
Taiwan	1	Antig	DMFCs	• Consumer electronics • Battery chargers • Portable power generators
	2	APFCT	PEMFCs	• LTVs
	3	M-Field	PEMFCs	• EPS • APUs
Denmark	1	H2 Logic	PEMFCs	• Material handling
	2	Serenergy	PEMFCs RMFCs	• EPS • APUs • Material handling • L-FCEVs • Battery chargers • Portable power generators
	3	Topsoe Fuel Cell	SOFCs	• Residential distributed CHP generation
France	1	BIC[h]	N/A	• Consumer electronics • Battery chargers
	2	Peugeot	PEMFCs	• APUs • L-FCEVs
	3	Renault	PEMFCs	• L-FCEVs
Switzerland	1	Hexis	SOFCs	• Residential distributed CHP generation
	2	MES	PEMFCs	• L-FCEVs • EPS • Aerial propulsion • UAVs • LTVs • Portable power generators

Table 9 (*continued*)

Country	#	Company	FC type(s)	Market(s)
Italy	1	SOFCpower	SOFCs	• Residential and commercial distributed CHP generation • RAPS
	2	Fiat[i]	PEMFCs	• L-FCEVs • H-FCEVs
Belgium	1	Van Hool	PEMFCs	• H-FCEVs
Finland	1	Convion[j]	SOFCs	• Residential distributed CHP generation
Estonia	1	Elcogen	SOFCs	• General-purpose stacks
Netherlands	1	Nedstack	PEMFCs	• EPS • RAPS • Material handling • H-FCEVs • Industrial and residential distributed CHP generation • Marine propulsion • LTVs • L-FCEVs
Australia	1	Ceramic Fuel Cells	SOFCs	• Residential and commercial distributed CHP generation • Residential and commercial distributed power generation
Singapore	1	Horizon	PEMFCs DMFCs	• UAVs • Consumer electronics • Battery chargers • Portable power generators • Toys and educational kits • RAPS • EPS • L-FCEVs
Greece	1	Tropical	PEMFCs	• H-FCEVs • Residential and commercial distributed CHP generation • Portable power generators • L-FCEVs • LTVs • EPS • RAPS

[a] On February 2013, ClearEdge Power acquired UTC Power.
[b] And its subsidiary Versa.
[c] And its subsidiary Sanyo.
[d] And its brand Mercedes-Benz.
[e] And its brands Audi and Skoda.
[f] On July 2012, Ballard acquired IdaTech.
[g] In June 2012, LG acquired Rolls-Royce Fuel Cell Systems.
[h] On November 2011, BiC acquired Angstrom Power.
[i] And its brand Chrysler.
[j] On January 2013, Wärtsilä fuel cell activities have been moved to a new company—Convion.

have been developed in Germany for the German and Italian navies [103]. The submarines use a hybrid power system consisting of a Siemens fuel cell system, diesel generator, and a high-voltage battery. Some remarkable advantages of fuel cell-based submarines are that they can stay underwater without surfacing for refueling much longer when compared to a conventional diesel electric submarine (the German submarines are able to stay underwater for weeks fueled by the stored oxygen and hydrogen in comparison to a limit of only two days if the propulsion system was purely diesel-based), have efficiencies as high as 70% due to the usage of pure oxygen as the oxidant in the fuel cell instead of air, have lower heat and magnetic signatures when compared to nuclear- or diesel-based submarines, and produce almost no noise due to the static operation of the fuel cell. These advantages make fuel cell-based submarines highly undetectable and ideal for modern military mission requirements, which encouraged the Italian, Greek, and South Korean navies to invest and take interest in fuel cell submarines as well [104].

Fig. 16 summarizes the main applications in the portable, stationary, and transportation sectors as per the above discussions. Table 9 lists the major fuel cell system solutions developers in the world with the types of fuel cell systems they develop, the company's country, and the targeted markets of their fuel cell systems solutions.

5. Current and future R&D

5.1. Current status

Indeed, the fuel cell industry has gone though many milestones and accomplishments in the past decade. For instance, the cost of fuel cells customized for fuel cell electric vehicles, projected to a production level of 500,000 units per annum, went through a cost reduction of 83% in the span of 2002–2012, from \$275/kW to \$47/kW [9]. This value jumps to \$219/kW if projected to a production level of only 1000

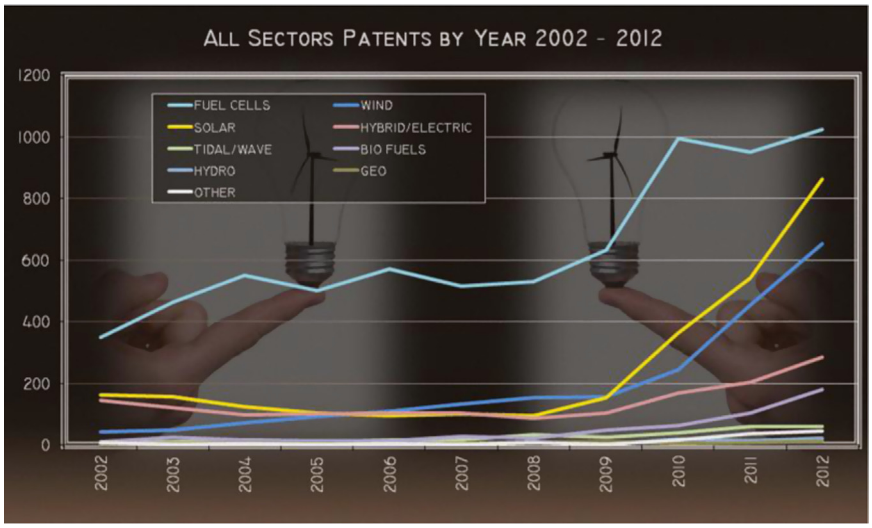


Fig. 17. Patents granted in the alternative energy sectors between 2002 and 2012 [107].

Table 10
Major fuel cell R&D milestones in the United States in 2012 (adapted from [105]).

R&D focus	2012 Milestone(s)
FC system cost[a]	A 4% cost reduction from 2011 ($49 to $47/kW) due to platinum-loading reduction, cell power density increase, ejector system modifications, improved system controller, radiator size reduction
FC system durability[b]	4000 h in laboratory testing was achieved (100% increase from 2006) due to modified anode and cathode catalysts with highly-active and durable oxygen evolution properties
Catalyst	• Development of dealloyed catalysts with high mass activity, high durability, and high cell voltage under high current density • Reduction of platinum-loading by 15% for nanostructured thin film (NSTF) catalysts to 0.14–0.18 g/kW
Portable FC	• Power density of direct dimethyl ether fuel cell improved by 60% from 2011, which approaches direct methanol fuel cells at low currents, due to a new anode catalyst • Mass activity of direct methanol fuel cell improved by 150% due to a new anode catalyst
BoP components	A novel composite membrane humidifier is projected to meet the target of $100 under mass production

[a] Projected at a production level of 500,000 units per annum.
[b] Defined as the time it takes the stack to lose 10% of its original voltage.

units per annum [105], emphasizing the impact mass production has on cost. One of the main reasons for this cost reduction was due to the continuous decrease in the platinum group metals (PGM) loading in PEM stacks. PGM-loading decreased by two orders of magnitude since the 1960s due to major development efforts in electrocatalyst fabrication and nanotechnology [106]. Patents granted in different alternative energy sectors between the years 2002 and 2012 were led in each single year by the fuel cell industry [107], as seen from Fig. 17. 44% of the patents in the fuel cell sector between 2002 and 2012 went to developers from the United States, followed by 33% in Japan, 7% in Korea, and 6% in Germany; with General Motors, Honda, Toyota, Samsung, and UTC Power securing more than 60% of these patents, in that order. The number of patents granted is a reflection of the level of industrial research taking place in the different renewable sectors. Table 10 lists some of the most important achievements fuel cell R&D went through in the year 2012 in the United States [105].

5.2. *Future targets*

Nonetheless, the industry still has a long way ahead in order to achieve the long-awaited goal of widespread commercialization. It is important to realize that advancements in fuel cell technology go hand-in-hand with advancements in hydrogen production, storage, and delivery technologies. With this relation in mind, we are still in-need for fundamental breakthroughs in material engineering, nanotechnology, transport phenomena, electrocatalysts engineering, stack engineering, measurement technologies, simulation of molecular processes, auxiliary components development, and multi-phase science in order to decrease the cost and increase the durability of fuel cells to meet future targets. For example, fundamental knowledge of liquid water formulation and interactions can ensure efficient water balance and avoid flow misdistribution which would enhance the fuel cell's performance and efficiency [28]. The key limitations facing the fuel cell industry that call for an R&D focus from both the industrial and academic communities include:

- identifying, modeling, and mitigating MEA degradation mechanisms;
- developing electrolyte materials that maintain conductivity and stability over a wide range of temperature and humidity;
- minimizing/eliminating catalysts PGM loading;
- maximizing membrane and catalyst impurities tolerance;
- identifying membrane and catalyst stability with voltage and humidity cycling;
- developing bipolar plate designs with reduced pressure drops, volume, and weight;
- developing durable seals, bipolar plates, and MEAs for high-temperature operation;

Table 11
Fuel cell R&D targets (adapted from [9,108]).

R&D focus	R&D targets
Electrolytes	• Develop electrolyte material (polymer, phosphoric/solid acid, solid oxide, molten carbonate, anion-exchange) with improved conductivity over temperature and humidity ranges • Develop electrolyte material (polymer, phosphoric/solid acid, solid oxide, molten carbonate, anion-exchange) with improved mechanical, thermal, and chemical stability over temperature and humidity ranges • Develop electrolyte material (polymer, phosphoric/solid acid, solid oxide, molten carbonate, anion-exchange) with reduced (or eliminated) fuel crossover over temperature and humidity ranges • Design ionomer membranes using scalable fabrication processes • Design ionomer membranes with reduced cost • Design ionomer membranes with improved mechanical, thermal, and chemical stability over temperature and humidity ranges • Evaluate membrane tolerance of air, fuel, and system impurities • Evaluate membrane mechanical stability with relative humidity cycling • Identify electrolyte mechanical and chemical degradation mechanisms • Develop mitigation strategies for electrolyte mechanical and chemical degradation mechanisms
Catalysts	• Develop catalysts with reduced (or eliminated) precious metal loading for low-, medium-, and high-temperature fuel cells • Develop catalysts with improved specific and mass activities • Develop catalysts with improved stability with potential cycling • Develop catalysts with tolerance of air, fuel, and system impurities • Develop non-PGM catalyst for PEM and anion-exchange membrane fuel cells • Increase catalysts utilization • Develop high-temperature fuel cell catalysts with improved activity and durability • Reduce corrosion of catalyst supports • Develop catalyst support material and structure with reduced cost • Develop catalyst supports with improved loading and thickness of non-PGM catalyst • Optimize catalyst/support interactions and microstructure • Develop anode catalyst for non-hydrogen fuel cells
GDLs	• Improve GDL pore structure, morphology, and physical properties • Improve GDL coating for better water management and more stable operation • Develop GDL material and structures with reduced area-specific resistance • Identify GDL corrosion and degradation mechanisms
MEAs and unit cells	• Optimize catalyst/support/ionomer/membrane mechanical and chemical interactions • Minimize MEA interfacial resistance • Integrate membranes, catalysts, and GDLs into unified MEAs • Integrate catalysts, supports, and electrolytes for high-temperature fuel cells • Address MEA freezing and thawing issues • Expand MEA operation temperature and humidity ranges • Improve MEA and cell stability under voltage and humidity cycling • Develop mitigation strategies for the effect of air, fuel, and system impurities • Characterize and test MEAs and cells before, during, and after fabrication and operation
Seals (gaskets)	• Develop seals for high-temperature fuel cells
Bipolar plates and interconnects	• Develop interconnects for high-temperature fuel cells • Develop electrolyte reservoir plates for phosphoric acid fuel cells • Decrease weight and volume of bipolar plates • Develop coatings for bipolar plates that eliminate corrosion • Develop bipolar plate materials and coatings for reduce cost • Identify bipolar plates mechanical and chemical degradation mechanisms • Develop mitigation strategies for bipolar plates mechanical and chemical degradation mechanisms
Stack-level operation	• Model stack impurities effects • Model stack durability and degradation • Model stack freezing and thawing effects • Model performance of upgraded stack components • Identify stack long-term failure modes using experimentation • Model stack mass transport and validate using experimental data • Optimize stack water management
BoP components	• Reduce cost of chemical and temperature sensors in stationary applications • Improve reliability and durability of chemical and temperature sensors in stationary applications • Meet packaging, cost, and performance requirements for air management mechanisms in stationary and transportation applications • Minimize parasitic load of air management mechanisms in stationary and transportation applications • Reduce noise level of air management mechanisms in stationary applications • Develop non-toxic coolants with low electrical conductivities • Increase efficiency, durability, and reliability of humidifiers in transportation applications • Develop humidifier materials and new humidification concepts for transportation applications • Minimize parasitic loads of humidifiers in transportation applications • Develop lightweight humidifier material with reduced cost in transportation applications

Table 11 (*continued*)

R&D focus	R&D targets
Fuel reformation	• Develop fuel-flexible reformers • Develop reformation catalysts and hardware that generate hydrogen-rich gas • Minimize fuel reformation cost • Improve reformers tolerance to impurities • Develop gas clean-up with low cost • Integrate subsystems of fuel reformers • Integrate thermal loads of fuel reformers • Eliminate hardware, piping, sensors, and controls from reactor
System-level operation	• Model system impurities effects • Model system durability and degradation • Minimize carbon dioxide migration in alkaline fuel cells • Improve start-up time and stability for high-temperature fuel cells
Performance characterization	• Perform cost analyses for automotive and bus applications • Perform cost analyses for emerging applications including auxiliary power units (APUs), emergency back-up systems, and material handling • Annually update technology status • Conduct tradeoff analysis between rated power and efficiency • Conduct tradeoff analysis between start-up energy and start-up time • Conduct tradeoff analysis between hydrogen quality and fuel cell performance and durability
Experimental testing and diagnostics	• Determine long-term stack failure modes using experimental methods • Determine system emissions using experimental methods • Characterize component and stack properties before, during, and after operation using experimental methods • Develop accelerated-testing mechanisms for durability in stationary applications

- developing air management techniques with reduced noise, cost, and parasitic loads;
- developing water management techniques capable of handling a wide range of operation conditions based on a better understanding of water transport phenomena;
- improving and simplifying fuel reformation methods;
- improving and unifying standards for accelerated testing; and
- conducting cost analyses for niche markets along with updated status reports.

Table 11 details the main targets for the ongoing fuel cell research and development efforts in the United States with respect to both individual components in a fuel cell stack and components in the fuel cell system. Table 12 summarizes the set future targets for fuel cell technology in the United States with respect to the different fuel cell markets in order for mass production and widespread commercialization of fuel cells to become practical goals instead of optimistic speculations.

6. Fuel cell design levels: The unit cell, the stack, and the system

The unit cell is the heart of a fuel cell system where the basic electrochemical reactions take place. The building blocks of a single unit cell are called the membrane electrode assemblies (MEAs). An MEA consists of the polymer membrane in-between two electrodes and two gas diffusion layers (GDLs), also known as the porous transport layers (PTLs) and the gas diffusion media (GDM). Each electrode is a thin electrocatalyst layer (usually platinum deposited on the surface of carbon-supported powder) attached to either the membrane or the gas diffusion layer, as shown in Fig. 18 [110]. This microscopic catalyst electrode layer is where the fuel cell′s electrochemical reactions take place. In this layer, the reactant gases coming from the GDL interact electrically and ionically with the electrolyte membrane with the help of the electrocatalyst electrodes.

The potential of a single unit cell is typically between 0.5 and 0.8 V, which is too small for most practical applications. Thus, several unit cells are connected in-series to form what is known as a fuel cell stack, as shown in Fig. 19 [111]. A fuel cell stack is significantly more complex than a single unit cell due to the requirements for current collection, thermal management, water management, humidification of gases, cell and gas separation, structural support, and oxidant and fuel distribution. In addition to the MEA, gas diffusion layers, heating and cooling plates, current collectors, end plates, clamping bolts, gaskets, insulators, and bipolar flow field plates are added to a fuel cell stack to satisfy these requirements, as shown in Fig. 20 [112]. The specific roles of each of these components in a PEMFC stack are described and listed in Table 13. Along with materials engineering, the variety of options and strategies for stack design and configuration has made stack engineering one of the most critical and challenging aspects for the successful commercialization of fuel cells.

A complete fuel cell system consists of the fuel cell stack in addition to the BoP subsystems. BoP subsystems are complementary components that provide the oxidant and fuel supply and storage, thermal management, water management, power conditioning, and instrumentation and control of the fuel cell system. The specific roles of each of these subsystems are described and listed in Table 14. A complete hydrogen-air PEMFC system is shown in Fig. 21 [113]. Usually, the complexity of the overall fuel cell system increases with increasing fuel cell stack size as the temperature, pressure, water, and heat become more problematic and demanding.

7. Thermodynamic and electrochemical principles of hydrogen fuel cells

In hydrogen fuel cells, the electrolyte conducts the H^+ ions from the anode to the cathode. The electrochemical reactions in a PEMFC occur simultaneously at the interfaces between the two catalyst layers and the membrane, as per Eqs. (1) and (2). Thus, H^+ passes through the proton-conductive acidic membrane from the

Table 12
Fuel Cell Commercialization Targets (Adapted from [108,109]).

Market	Characteristics	Unit	Current Status	Future Target
80 kWe Automotive Transportation[a]	Electric Efficiency[b]	%	59	60
	Power Density	$W\text{-}L^{-1}$	400	850
	Specific Power	$W\text{-}kg^{-1}$	400	650
	Cost[c]	$\$\text{-}kW_e^{-1}$	49	30
	Cold Start-Up Time at –20 °C[d]	s	20	30
	Cold Start-Up Energy at -20 °C[e]	MJ	7.5	5
	Cold Start-Up Time at 20 °C[d]	s	< 10	5
	Cold Start-Up Energy at 20 °C[e]	MJ	N/A	1
	Durability[f]	h	2,500	5,000
1–10 kWe Small Residential CHP[g]	Electric Efficiency[h]	%	30–40	> 45
	CHP Efficiency[i]	%	80–90	90
	Cost[j]	$\$\text{-}kW_e^{-1}$	2,300–4,000	1,500
	Dynamic Response Time[k]	min	5	2
	Cold Start-Up Time at 20 °C	min	< 30	20
	Degradation Rate[l]	$\frac{\text{power loss\%}}{\text{1,000 hours}}$	2	0.3
	Durability[m]	h	12,000	60,000
	Availability[n]	%	97	99
100–3,000 kWe Medium CHP[o]	Electric Efficiency[h]	%	42–47	> 50
	CHP Efficiency[i]	%	70–90	90
	Equipment Cost for Natural Gas Fuel[p]	$\$\text{-}kW_e^{-1}$	2,500–4,500	1,000
	Equipment cost for Biogas Fuel[p]	$\$\text{-}kW_e^{-1}$	4,500–6,500	1,400
	Number of Lifetime Outages[q]	–	50	40
	Durability[r]	h	40,000–80,000	80,000
	Availability[n]	%	95	99
< 2 W Micro Portable[s]	Specific Power	$W\text{-}kg^{-1}$	5	10
	Power Density	$W\text{-}L^{-1}$	7	13
	Specific Energy	$Wh\text{-}kg^{-1}$	110	230
	Energy Density	$Wh\text{-}L^{-1}$	150	300
	Cost[t]	$\$\text{-system}^{-1}$	150	70
	Durability[u]	h	1,500	5,000
	MTBF[v]	h	500	5,000
10–50 W Small Portable[s]	Specific Power	$W\text{-}kg^{-1}$	15	45
	Power Density	$W\text{-}L^{-1}$	20	55
	Specific Energy	$Wh\text{-}kg^{-1}$	150	650
	Energy Density	$Wh\text{-}L^{-1}$	200	800
	Cost[w]	$\$\text{-system}^{-1}$	15	7
	Durability[u]	h	1,500	5,000
	MTBF[v]	h	500	5,000
100–250 W Medium Portable[s]	Specific Power	$W\text{-}kg^{-1}$	25	50
	Power Density	$W\text{-}L^{-1}$	30	70
	Specific Energy	$Wh\text{-}kg^{-1}$	250	640
	Energy Density	$Wh\text{-}L^{-1}$	300	900
	Cost[x]	$\$\text{-system}^{-1}$	15	5
	Durability[u]	h	2,000	5,000
	MTBF[v]	h	500	5,000
1–10 kWe APU[ag]	Electric Efficiency[y]	%	25	40
	Power Density	$W\text{-}L^{-1}$	17	40
	Specific Power	$W\text{-}kg^{-1}$	20	45
	Factory Cost[z]	$\$\text{-}kW^{-1}$	2,000	1,000
	Dynamic Response Time[k]	min	5	2
	Cold Start-Up Time at 20 °C	min	50	30
	Standby Start-Up Time	min	50	5
	Degradation Rate[aa]	$\frac{\text{power loss\%}}{\text{1,000 hours}}$	2.6	1
	Durability[ab]	h	3,000	20,000
	Availability[ac]	%	97	99
Transit Buses[ad]	Equivalent Mileage	miles per gallons diesel-equivalent	7	8
	Maintenance Cost[q]	$\$\text{-mile}^{-1}$	1.20	0.40
	Operation Time	$h\text{-week}^{-1}$	133	140
	Power System[ae] Cost[af]	$	700,000	200,000
	Bus Cost[af]	$	2,000,000	600,000
	Availability	%	60	90
	Power System Durability	h	12,000	25,000
	Bus Durability	years	5	12

[a] For a direct-hydrogen PEM fuel cell system excluding hydrogen storage, power electronics, and the electric drive with current statues in 2011 and future targets set in 2020.
[b] Defined as $\frac{\text{DC output energy}}{\text{LHV of hydrogen}}$ at 25% rated power (which corresponds to the peak efficiency).
[c] Projected at a production level of 500,000 units per annum.
[d] To 50% rated power.
[e] Defined as the energy consumed from cold start to 50% rated power based on LHV of hydrogen.
[f] Defined as the time it takes the stack to lose 10% of its original voltage.
[g] Fuel cell system operating on natural gas delivered through pipelines at typical distribution pressure with current statues in 2011 and future targets set in 2020.
[h] Defined as $\frac{\text{regulated AC output energy}}{\text{LHV of fuel}}$.
[i] Defined as $\frac{\text{regulated AC output energy+useful recovered thermal energy}}{\text{LHV of fuel}}$ where domestic space and water heating are the useful applications for the recovered thermal energy.

[j] Projected at a production level of 500,000 units per annum for a system with an average AC output of 5 kW_e while the system is running where cost includes all CHP system components and equipment (with taxes and markup).

[k] Defined as the time it takes the system to respond to a 10% to 90% rated power demand change.

[l] Where transient operation effects are included in the degradation tests.

[m] Defined as the time it takes the system to lose > 20% of its original net power.

[n] Defined as the percentage of time the system is available for realistic operation (system unavailability due to maintenance etc.).

[o] Fuel cell system, including fuel processor and auxiliary equipment, operating on natural gas delivered through pipelines at typical distribution pressure (current status vary according to the used technology) with current statues in 2011 and future targets set in 2020.

[p] Where current cost is for the current ~30 MW per year production rate and future target cost is projected to ~100 MW per year both without installation costs.

[q] Planned and forced.

[r] Defined as the time it takes the system to lose > 10% of its original net power.

[s] Fuel cell system (technology and fuel neutral) with current statues in 2011 and future targets set in 2020.

[t] Projected at a production level of 50,000 units per annum with installation costs included.

[u] Defined as the time it takes the system to lose 20% (somewhat variable with application) of its original net power where transient operation effects and offline degradation are included in the durability tests (tests are application-specific).

[v] Mean Time Between Failures (MTBF) due to failure of any system component where transient operation effects and offline degradation are included in tests.

[w] Projected at a production level of 25,000 units per annum with installation costs included.

[x] Projected at a production level of 10,000 units per annum with installation costs included.

[y] Defined as $\frac{\text{regulated DC output energy}}{\text{LHV of fuel}}$.

[z] Projected at a production level of 50,000 units per annum for a system with an output of 5 kW where the cost includes material and labor to produce a complete system.

[aa] Where considerations for daily standby cycles, weekly shutdown cycles, exposure to vibrations, and variable operation condition are included in the degradation tests.

[ab] Defined as the time it takes the system to lose > 20% of its original net power where considerations for daily standby cycles, weekly shutdown cycles, exposure to vibrations, and variable operation condition are included in the durability tests.

[ac] Defined as the percentage of time the system is available for realistic operation (system unavailability due to scheduled maintenance non-applicable).

[ad] Fuel cell (including auxiliary systems, power electronics, and hydrogen storage) and battery hybrid system with current status in 2012 and future targets set for the commercialization stage.

[ae] Defined for both the fuel cell system and the battery system.

[af] Projected at a production level of 700 units per annum.

[ag] Fuel cell system running on ultra-low sulfur diesel fuel with current statues in 2011 and future targets set in 2020.

anode to the cathode in response to the reactive attraction of hydrogen to oxygen, while e^- travels through an external circuit from the anode to be consumed at the cathodic reaction. The current of the e^- traveling through the external circuit gives us useful electrical work. At the cathode, O_2 from the cathodic flow, H^+ that passed through the membrane, and e^- that passed through the external circuit all combine to form water. This water could be partially or completely removed with the cathodic outlet flow and could be in liquid or vapor form; depending on many interrelated factors such as the operation temperature, stoichiometric ratio of reactants, and design of the flow fields. Water accumulation at the cathode usually requires proper water and thermal management in order for the stack's performance not to decline. Thus, the overall electrochemical exothermic reaction is as per Eq. (3).

7.1. Reversible efficiency

The enthalpy of the overall chemical reaction in a fuel cell is the difference between the enthalpies of formation of the products and reactants. This enthalpy of formation represents the amount of heat energy produced from the complete combustion of the hydrogen fuel and will serve an important purpose when we define the reversible efficiency of a fuel cell. On a unit mole basis, the enthalpy of formation in a hydrogen fuel cell is given by

$$\Delta H_f = (h_f)_{H_2O} - (h_f)_{H_2} - (h_f)_{O_2} \tag{6}$$

The enthalpy of formation of elements such as oxygen and hydrogen is zero by definition while the enthalpy of formation of water can be calculated at different temperatures. Thus, Eq. (6) reduces to

$$\Delta H_f = (h_f)_{H_2O} \tag{7}$$

As per Eq. (3), if the product water is in liquid form, then we will be referring to the HHV of the enthalpy of formation. However, if the product water is in vapor form, then we are referring to the LHV of the enthalpy of formation. The difference between these two values is water's molar latent heat of vaporization.

However, since combustion oxidation does not occur within a fuel cell, the enthalpy of formation serves only as an indicator of the amount of energy input to a fuel cell. Neglecting work done for the change of pressure and/or volume, the maximum portion of the energy input to a fuel cell that could be converted into useful electric work is found from the Gibbs free energy of formation, which is given on a mole basis using:

$$\Delta G_f = \Delta H_f - T\Delta S_f \tag{8}$$

The entropy of formation for the reaction can be calculated in a similar way to the enthalpy of formation at different temperatures by the following equation:

$$\Delta S_f = (s_f)_{H_2O} - (s_f)_{H_2} - (s_f)_{O_2} \tag{9}$$

It is important to distinguish that ΔG_f is the maximum useful work associated with a chemical reaction while ΔH_f is the maximum heat associated with a chemical reaction. When all the ΔG_f is converted into useful electric work by moving electrons through an external circuit, the cell voltage is termed the reversible cell voltage. Finally, when considering Eq. (8), it is important to realize that the $T\Delta S_f$ term grows faster than the ΔH_f term with an increase in temperature. Thus, we expect ΔG_f to decrease in magnitude as temperature is increased.

In order to define a maximum efficiency concept similar to the Carnot efficiency in heat engines, we have to consider both the energy input to the fuel cell system and the maximum amount of that energy available to do external work. The former is the enthalpy of formation and the latter is the Gibbs free energy of formation, as per the above discussion. Thus, we can define the reversible maximum efficiency of a fuel cell as the ratio between these two variables, as follows:

$$\eta_{rev} = \frac{\Delta G_f}{\Delta H_f} \tag{10}$$

Fig. 22 compares the ideal theoretical efficiency of a fuel cell against that of a Carnot engine. We observe that at the lower and

intermediate operating temperatures, the fuel cell ideal efficiency is significantly better. While at higher operating temperatures, both ideal efficiencies are close to each other. The practical implementation of a lower operating temperature is better dynamic response and quicker load-up times for applications. However, in reality, operation at higher operation temperatures results in higher cell voltage due to reduced voltage losses, as will be seen in later sections.

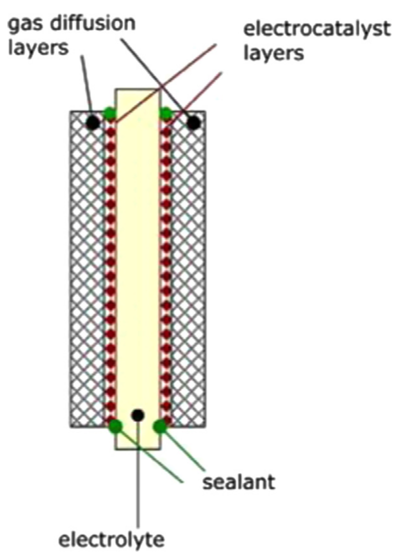


Fig. 18. Membrane electrode assembly [110].

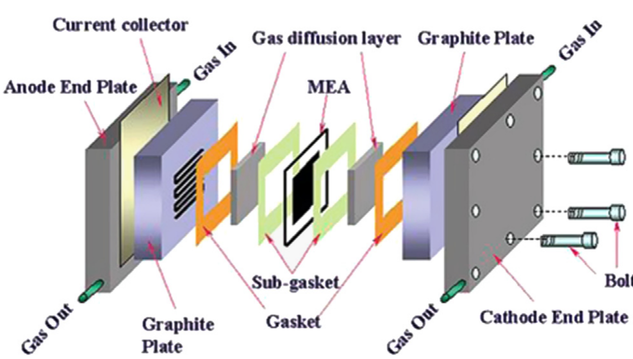


Fig. 19. Single unit cell and a stack of cells [111].

7.2. Reversible voltage

Electrical work is defined as the product of charge and potential as

$$W_{ele} = qE \tag{11}$$

The total charge transferred with electrons in a fuel cell per every mole of H_2 is

$$q = n\, N_{avg}\, q_{el} \tag{12}$$

where n, N_{avg}, and q_{el} are the number of electrons per molecule of H_2 involved in the reaction, Avogadro's number, and the charge of an electron, respectively. Eq. (12) can be further simplified by noting that the product of N_{avg} and q_{el} is the electric charge per mole of electrons, or in other words equal to Faraday's constant (96,485 C/electron-mole). Thus, the electrical work could be expressed as

$$W_{ele} = nFE \tag{13}$$

However, we saw that the Gibbs free energy of formation is equal to the electric work produced in a fuel cell when the system has no irreversibilities. Accordingly, W_{ele} is equal to $-\Delta G_f$ in a reversible system and we can express the reversible cell voltage in a fuel cell as

$$E_{rev} = -\frac{\Delta G_f}{nF} \tag{14}$$

The above value is the highest theoretically attainable voltage from an isothermal fuel cell and is commonly called the Nernst voltage. It is worth noting that if we replace the Gibbs free energy in Eq. (14) with enthalpy, we get what is known as the thermo-neutral cell voltage, which corresponds to the complete conversion of all the energy content in the fuel to electric work (i.e., 100% thermal efficiency and no internal thermal energy generation). Substituting Eq. (8) into Eq. (14) yields:

$$E_{rev} = \frac{\Delta H_f - T\Delta S_f}{nF} \tag{15}$$

As we can see from Eq. (15) and from Fig. 23, increasing the temperature would result in a decrease in the theoretical potential of the fuel cell. However, mass transport and ionic conduction are faster at higher temperatures and this more than offsets the drop in the Nernst voltage, as will be seen in later sections. Using the definition of reversible cell voltage in Eq. (15), we can define the voltage efficiency of a fuel cell as

$$\eta_{vol} = \frac{E}{E_{rev}} \tag{16}$$

where E is the operating voltage. That is, the voltage efficiency is the ratio of the cell operating voltage to the Nernst voltage.

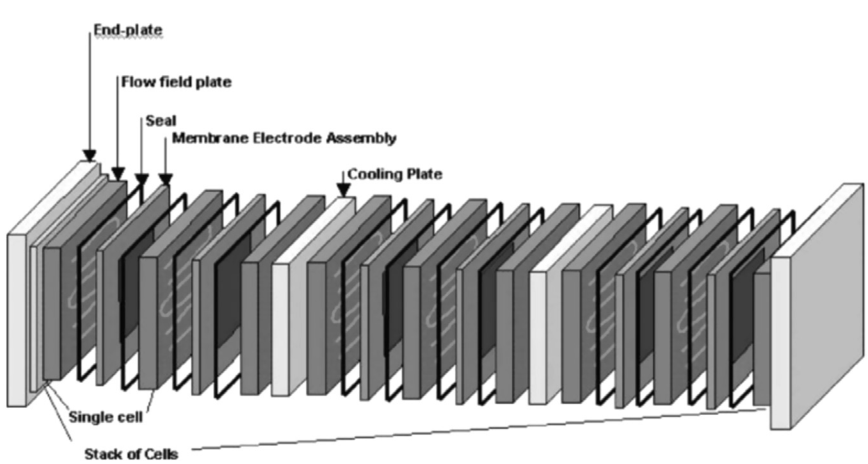


Fig. 20. Main components in a fuel cell stack [112].

Table 13
PEMFC stack components and their functions.

Component	Function
MEA	
Proton exchange membrane (electrolyte)	• Enables the protons to travel from the anode to the cathode. • A film barrier between the oxidation and reduction half reactions.
Electrocatalyst (electrode)	• Stimulates the oxidation and reduction reactions.
Gas diffusion layer	• Allows direct and uniform diffusion of hydrogen and oxygen to the catalyst layer (electrode). • Allows conduction of electrons to and from the catalyst layer. • Allows water formed at the cathode layer to exit. • Allows heat generated from the electrochemical reactions in the catalyst layer to exit. • Provides structural support to the "flimsy" MEA.
Flow field (bipolar) plate	• Channels oxygen and hydrogen to the electrodes via flow channels. • Channels water and heat away from the fuel cell. • Collects and conducts electrical current in-series. • Separates the gases in adjacent cells. • Forms the inner supporting structure of the fuel cell stack.
Gasket	• Aids in keeping the reactant gases in their respective regions in each cell.
Current collector	• Collects the current and passes it to/from the external circuit.
End plate	• Provides sufficient contact pressure in the stack to prevent leaking of reactants and to minimize the contact resistance between different layers.
Heating and cooling plates and manifold	• When the stack size is large, heating and cooling plates are internally used (between every 2–4 cells) to keep the stack's temperature near its optimum operating temperature.
Reactant gases manifold	• Feeds, externally or internally, each cell in the stack with oxygen and fuel.

Table 14
PEMFC balance-of-plant subsystems.

Subsystem	Function
Water management	• Ensures all parts of the fuel cell are sufficiently hydrated without flooding. • Humidifies the incoming gases (especially to the anode). • Ensures proper water removal from the cathode. • Employs purge cycles and back pressure regulators for the removal of accumulated liquid water from the anode.
Thermal management	• Uses fans for active air cooling. • Uses pumps for circulation of cooling liquid through cooling plates. • Provides start-up heating in cold climates if required.
Gases management	• Employs an appropriate storage mechanism for hydrogen storage with pressure-reducing regulators. • Uses a fuel cell reformer in case of using hydrocarbons as hydrogen sources. • Employs a pump for hydrogen recirculation. • Employs a fan, blower, or compressor for air supply.
Power conditioning	• Converts the variable low-DC voltage output to usable DC power via a step-up DC–DC converter when required. • Inverts the variable low-DC voltage output to usable AC power via a switch-mode DC–AC inverter when required. • Employs a battery or an ultracapacitor to meet the power spike transients.

So far, we have approximated the Gibbs free energy of formation as a function of temperature only, as per the discussions above. However, Gibbs free energy is a function of both temperature and pressure. This is evident when Gibbs free energy of formation for a hydrogen fuel cell is expressed according to the following more accurate thermodynamic equation:

$$\Delta G_f = \Delta G_f^0 - RT \ln\left(\frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2O}}\right) \tag{17}$$

where the 0 superscript indicates standard conditions and the P's are the gases partial pressures (proportional to the molar fractions in a mixture and assuming all species are in gaseous form). If we use the expression in Eq. (17) with the reversible voltage definition in Eq. (14), we get:

$$E_{rev} = E_{rev}^0 + \frac{RT}{nF} \ln\left(\frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2O}}\right) \tag{18}$$

where E_{rev}^0 is the reversible Nernst voltage at standard conditions. Thus, we observe from Eq. (18) that the partial pressures of the reactants and products play a significant role in changing the reversible Nernst cell voltage according to the concentration of the reactants and the products during the reaction. For instance, we

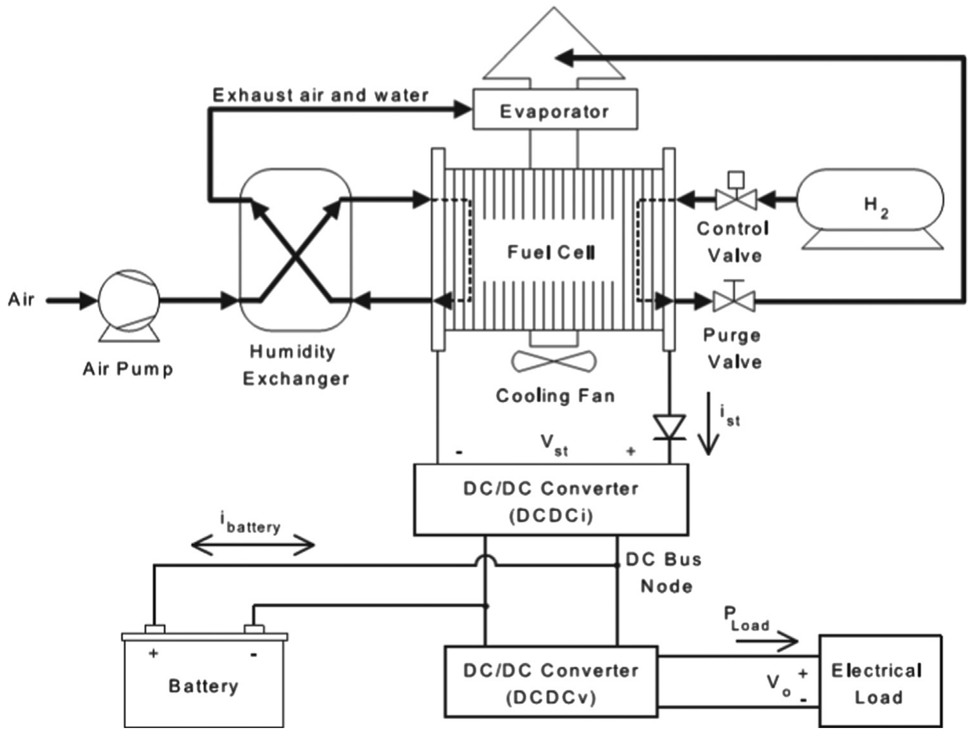


Fig. 21. A complete hydrogen-air PEM fuel cell system [113].

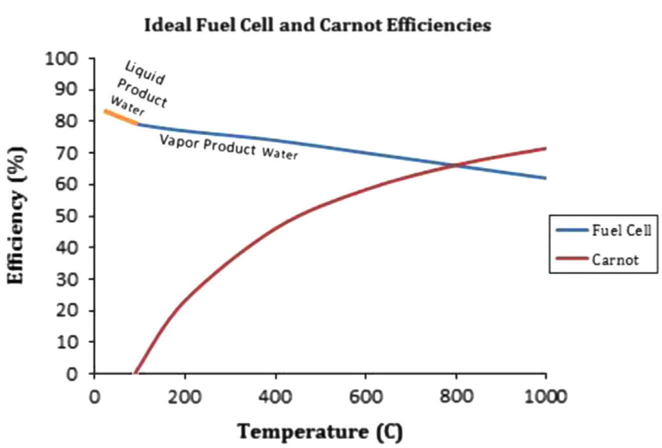


Fig. 22. Ideal fuel cell (using LHV) and Carnot efficiencies (using exhaust temperature of 90 °C) as a function of temperature.

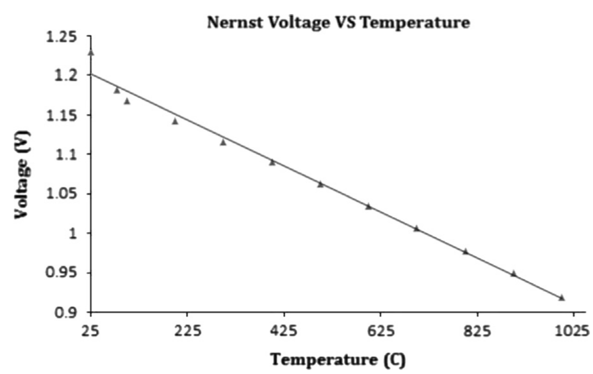


Fig. 23. Nernst voltage as a function of temperature for a hydrogen/oxygen PEMFC at 1 atm reactants pressure.

can use Eq. (18) to find that the effect of changing the inlet pressure or the concentration of hydrogen (e.g., pure or with traces of CO_x), which will be equal to:

$$\Delta E_{rev} = \frac{RT}{nF} \ln \frac{(P_{H_2})_2}{(P_{H_2})_1} \tag{19}$$

Thus, when the reactants contain inert diluents, the diluents will cause a drop in the reversible cell voltage referred to as the Nernst loss. We can also use Eq. (18) to isolate the effect of changing the system's pressure from P_1 to P_2 on the reversible cell voltage, which will be equal to:

$$\Delta E_{rev} = \frac{RT}{2nF} \ln \frac{P_2}{P_1} \tag{20}$$

Finally, we can use Eq. (18) to identify the effect of changing from air to pure oxygen on the reversible cell voltage, which will be equal to:

$$\Delta E_{rev} = \frac{RT}{2nF} \ln \frac{1.0}{0.21} \tag{21}$$

7.3. Flow rates

The amount of hydrogen and oxygen consumed in a fuel cell stack are a function of the current obtained from said stack. We can use Faraday's law to derive the relation between required flow rates of reactants for a specified current, where:

$$It = nzF \tag{22}$$

where I, t, n, z, and F are current in A, time in seconds, number of moles, number of electrons in the reaction, and Faraday's constant, respectively. Based on the reactions at the anode (Eq. (1)) and the cathode (Eq. (2)) for a hydrogen fuel cell and since z will be equal to 2 in this case, the molar flow rates of the reactants can be

calculated as follows:

$$\dot{n}_{hydrogen} = \frac{I}{2F} \quad (23)$$

$$\dot{n}_{oxygen} = \frac{I}{4F} = \frac{\dot{n}_{hydrogen}}{2} \quad (24)$$

where $\dot{n}$ is the molar flow rate in mol s^{-1}. Taking into account stoichiometric ratios, number of cells per stack, and the generalized case where the fuel and oxidant are not pure; we get the following more practical equations for the required molar flow rates of fuel and oxidant given a certain current output:

$$\dot{n}_{fuel} = \frac{IS_{H_2}N_{cell}}{2Fr_{H_2}} \quad (25)$$

$$\dot{n}_{oxidant} = \frac{IS_{O_2}N_{cell}}{4Fr_{O_2}} \quad (26)$$

where N_{cell} is the number of unit cells, S is the stoichiometric ratio, and r is the volume/molar fraction. In order to determine the molar flow rate of the water content in the fuel exhaust $((\dot{n}_{H_2O})_{fuel,\ out})$, we observe that it is going to be equal to the water content in the fuel inlet $((\dot{n}_{H_2O})_{fuel,\ in})$, plus the water transported from the cathode to the anode as a result of back diffusion $((\dot{n}_{H_2O})_{BD})$, less the water transported from the anode to the cathode as a result of electroosmotic drag $((\dot{n}_{H_2O})_{ED})$. Accordingly

$$(\dot{n}_{H_2O})_{fuel,\ out} = (\dot{n}_{H_2O})_{fuel,\ in} + (\dot{n}_{H_2O})_{BD} - (\dot{n}_{H_2O})_{ED} \quad (27)$$

Similarly, the molar flow rate of the water content in the oxidant exhaust $((\dot{n}_{H_2O})_{oxidant,\ out})$ is going to be equal to the water content in the oxidant inlet $((\dot{n}_{H_2O})_{oxidant,\ in})$, plus the water generated at the cathode $((\dot{n}_{H_2O})_{gen})$, plus the water transported from the anode to the cathode as a result of electroosmotic drag $((\dot{n}_{H_2O})_{ED})$, less the water transported from the cathode to the anode as a result of back diffusion $((\dot{n}_{H_2O})_{BD})$. Accordingly

$$(\dot{n}_{H_2O})_{oxidant,\ out} = (\dot{n}_{H_2O})_{oxidant,\ in} + (\dot{n}_{H_2O})_{gen} + (\dot{n}_{H_2O})_{ED} - (\dot{n}_{H_2O})_{BD} \quad (28)$$

Usually, we express back diffusion as a fraction of electroosmotic drag across a membrane. This is because back diffusion depends (in addition to other factors) on the water concentration gradient across the membrane, which is not uniform and difficult to model. While on the other hand, electroosmotic drag depends only on the current drawn. Accordingly, we can use the following to find both terms:

$$(\dot{n}_{H_2O})_{ED} = \xi\frac{IN_{cell}}{F} \quad (29)$$

$$(\dot{n}_{H_2O})_{BD} = \beta\xi\frac{IN_{cell}}{F} \quad (30)$$

where ξ is number of water molecules per proton and β is the fraction used to express back diffusion in terms of electroosmotic drag.

7.4. Fuel cell polarization

As mentioned earlier, the reversible cell voltage is the voltage that can be obtained if the Gibbs free energy could be converted directly into electrical work without any losses. However, in reality, there are several irreversibilities within a fuel cell that cause the actual cell voltage to be less than the reversible cell voltage. These irreversibilities cause the actual voltage to decline as current density increases. Thus, it is useful to plot cell voltage against current density as a merit of characterization for a certain fuel cell. And even at the open-circuit voltage state where no load exists, the actual voltage is still less than the reversible voltage. These irreversibilities are known as cell polarizations and could be divided into four main polarization sources; namely, crossover, activation, ohmic, and concentration losses, as depicted in Fig. 24. These polarization sources are active throughout the entire polarization curve. However, they become dominant at certain segments of the polarization curve, as will be shown in the following discussions. The polarization curve shown in Fig. 24 is one of the most important merits of evaluation in fuel cell science and when the four main polarizations are deducted from the reversible voltage we get what is known as the polarization equation:

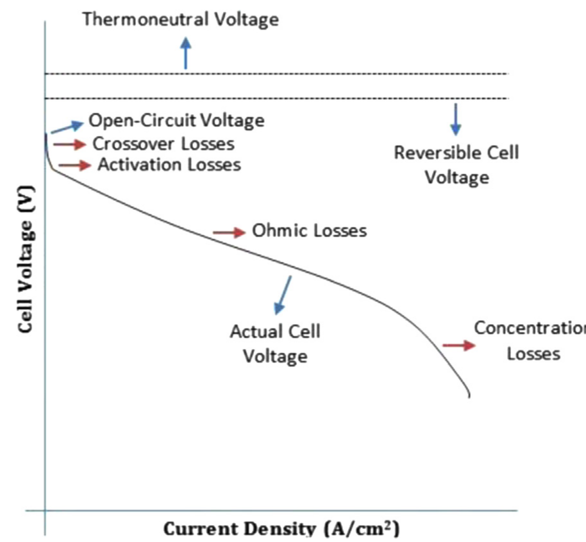


Fig. 24. Typical polarization curve with voltage losses.

$$E = E_{rev} - E_{a,\ a} - E_{a,\ c} - E_o - E_{c,\ a} - E_{c,c} \quad (31)$$

where $E_{a,\ a}$ and $E_{a,\ c}$ are the activation and crossover losses at the anode and cathode, E_o are the ohmic losses, and $E_{c,\ a}$ and $E_{c,\ c}$ are the concentration losses at the anode and cathode. All the terms in Eq. (31) need to be positive.

Activation polarization is the main cause of voltage drop at low current densities and is caused by sluggish oxidation and/or reduction kinetics at the electrodes surface. Initiating the electrochemical reactions requires energy that is reflected in the activation voltage drop. The activations losses at the anode and cathode could be isolated and expressed using Tafel′s equation:

$$E_{a,\ a} = A_a \ln\left(\frac{i}{i_{0,\ a}}\right) \quad (32)$$

$$E_{a,\ c} = A_c \ln\left(\frac{i}{i_{0,\ c}}\right) \quad (33)$$

where i is the current density, i_0 is the exchange current density, and A is given from:

$$A = \frac{RT}{n\alpha F} \quad (34)$$

where α is a constant known as the charge transfer coefficient which depends on the electrode′s material, microstructure, and reaction mechanism. The exchange current density is defined as the rate at which the simultaneous oxidation and reduction reactions occur under equilibrium conditions when the net current is zero. Thus, it is a measure of the electrode′s activity and the higher its value, the easier it is for a charge to move from/to the electrode to/from the electrolyte and the greater the current density. The exchange current density is the determining factor in activation losses. Its value is best given using the following equation [114]:

$$i_o = i_o^{ref}\varepsilon_c P_r^{\gamma}\exp\left(-\frac{E_c}{RT}(1-T_r)\right) \quad (35)$$

where i_o^{ref} is the exchange current density at arbitrary reference conditions, ε_c is the electrode reference (typically between 180 and 500), P_r is the ratio between the reactant partial pressure and the reactant reference pressure, γ is the pressure coefficient (typically between 0.5 and 1.0), E_c is the activation energy (equal to 66 kJ mol^{-1} for oxygen reduction on platinum), and T_r is the ration between the temperature and the reference temperature.

We always desire to maximize the value of the exchange current density in order to minimize the activation losses, as evident from Eqs. (32) and (33). As evident from Eq. (35), we can increase the value of the exchange current density by choosing an active electrode catalyst, increasing the operation temperature, increasing the operation pressure, increasing the roughness of the surface area of the electrodes to increase the active reaction sites, increasing the catalyst loading, and increasing the reactants concentration to increase the active spots on the electrodes surface area. Other factors that increase the activation losses due to catalyst degradation include the presence of catalyst contaminants in the reactants and prolonged loading cycles. It is important to notice that different activation losses occur at each electrode, hence, the two different terms in Eq. (31). Nevertheless, the current that passes through the two electrodes is the same. In hydrogen fuel cells, the reduction activation losses dominate. This is because the exchange current density for the reduction reaction is much less than that for the oxidation reaction. Accordingly, we are mostly concerned with increasing the exchange current density for the reduction reaction. It is interesting to notice that even though we witnessed previously that at higher temperatures the reversible cell voltage is lower; this is not the case for the actual cell voltage. The fact that activation losses decrease as temperature increases (as a result of the increased exchange current density, as per Eqs. (32), (33), and (35)) causes the actual cell voltage to actually increase with increased temperature. And even though the value of A in Eq. (34) will increase with increased temperatures, the increase in the exchange current density more than offsets the increase in A. Accordingly, the end result is usually less activation voltage losses as a result of increased temperatures. Thus, the actual cell voltage curve is shifted up while the reversible cell voltage is shifted down as a result of increased temperatures and the gap between them is lessened.

Crossover polarization is the main cause of voltage loss at open-circuit conditions and is due to two reasons. The first is the direct hydrogen fuel diffusion from the anode to the cathode through the electrolyte without the anodic reaction taking place, even though the membrane is practically impermeable to the hydrogen fuel. The second is the internal passing of electrons through the electrolyte rather than through the external circuit, even though the membrane is practically impermeable to electrons. The effect of these two phenomena is the same on the cell voltage (i.e., a voltage drop due to wasted hydrogen fuel and/or electrons). Crossover polarization is usually noticeable when the operation temperature is low and we are at or near the open-circuit conditions. This is because at open-circuit the only hydrogen fuel consumption occurring is due to crossover polarization while at closed-circuit the hydrogen consumed to generate the useful external current is much greater than that consumed (or wasted) as a result of the internal current. Moreover, the hydrogen concentration gradient across the membrane decreases with higher current densities due to the higher rates of hydrogen consumption at the anode. Thus, the driving force for the hydrogen molecules to diffuse through the membrane (i.e., the hydrogen concentration gradient) is weak at high current densities and strongest when no external current is drawn (i.e., at open-circuit conditions). As a result, crossover losses could be isolated and measured by measuring the small reactants consumption at open-circuit conditions when no external current is running.

So if we use Eq. (23) and divide by cell active area, we can express the internal current density at open-circuit conditions due to crossover polarization in a hydrogen fuel cell as

$$i_{loss} = \frac{2F\dot{n}_{hydrogen}}{A} \tag{36}$$

Accordingly, the lost internal current density due to crossover polarization could be incorporated into Eqs. (32) and (33) to yield:

$$E_{a,\,a} = A_a \ln\left(\frac{i_{loss}+i}{i_{0,\,a}}\right) \tag{37}$$

$$E_{a,\,c} = A_c \ln\left(\frac{i_{loss}+i}{i_{0,\,c}}\right) \tag{38}$$

This explains why the actual voltage is always less than the reversible voltage, as per Eq. (31). That is, the terms in Eqs. (37) and (38) will not be equal to zero at open-circuit conditions due to the lost internal currents. As a result, the open-circuit voltage will always be less than the reversible Nernst voltage, as depicted in Fig. 24. Nevertheless, it is possible to minimize crossover losses by optimizing the membrane's permeability and thickness.

The ionic and electric resistance of the stack's components to the flow of charge results in ohmic polarization. The electrolyte, catalyst layer, GDL, flow field plates, current collectors, interfacial contacts between the components, and the terminal connections all contribute to these ohmic voltage losses. The electric resistivity is due to the resistivity of the electrically-conductive cell components to the electrons flow while the ionic resistivity is due to the resistivity of the membrane to the ions flow. Most of the electric resistivity occurs due to the lack of proper contact between the GDL, bipolar plates, cooling plates, and other interconnects. However, usually, the ionic resistivity dominates ohmic voltage losses. This is because the number of charge carriers through an ionic conductor is much less than in an electronic conductor. In an electronic conductor, the valence electrons of the atoms become detached and can move freely, whereas in ionic conductors, the ions move through the vacancies in the crystallographic lattice. Thus, the electronic resistance is usually negligible in comparison to the ionic and contact resistances.

We can express the ohmic voltage losses due to ionic, contact, and electronic resistances according to Ohm's law as

$$E_o = i(R_{ele} + R_{ion} + R_{CR}) \tag{39}$$

where R_{ele}, R_{ion}, and R_{CR} are the area-specific electronic, ionic, and contact resistances in Ω cm^2. Ohmic losses are dominant at the middle of the polarization curve and affect all types of fuel cells. Thus, in order to minimize the ohmic losses, it is important to design the stack from materials with high conductivities (i.e., low resistivities), components with minimum thicknesses, and interconnects with minimum contact resistances through the optimization of the stack's compression pressure. This is particularly important for the electrolyte due to its dominant ionic resistivity. This could be achieved by designing a chemically and mechanically stable electrolyte with the highest possible conductivity and the smallest possible thickness since the resistivity of the electrolyte is proportional to the ratio of its thickness over conductivity. Also, the electrolyte material and water content play a significant role in determining its resistivity and need to be carefully considered.

Concentration polarization is dominant at high current densities and occurs when the electrode reactions are hindered by reduced reactants availability (i.e., concentration) at reaction sites. This concentration reduction (which translates to a partial pressure reduction) could be due to limited hydrogen fuel supply, limited diffusion rate of the fuel and oxidant from flow field channels to the catalyst layer, poor air circulation at the cathode which leads to nitrogen (or any other nonparticipating inert gases for that matter) build-up, water accumulation and flooding at the cathode and anode (especially for PEMFCs), or impurities

adsorption on electrode reaction areas. However, the cathode's concentration polarization usually dominates since water accumulation usually occurs at the cathode, nitrogen build-up also usually occurs at the cathode, and the diffusion rate of oxygen is much lower than that of hydrogen. It is possible to minimize concentration voltage losses by proper water management, removal of impurities, optimizing the stoichiometric ratio, and optimizing the thickness and porosity of the GDL.

In order to describe the concentration voltage losses, we note that the maximum current density the fuel cell can produce occurs when the rate of reactant (i.e., the fuel or the oxidant) consumption is equal to the rate of reactant supply. Thus, at this maximum current density the concentration of the reactant (i.e., its partial pressure) at the surface of the catalyst would reach zero. Similarly, the maximum concentration of the reactant (i.e., its maximum partial pressure) occurs when the current density drawn is zero. Assuming we have a linear relationship between the partial pressure of the reactant and current density generated, we come up with the following simple linear equation that relates the two variables (applicable to fuel and oxidant):

$$P = -\frac{P_{max}}{i_{max}} i + P_{max} \tag{40}$$

where P_{max} is the maximum partial pressure corresponding to the maximum concentration, i_{max} is the maximum current density, P is any pressure between zero and P_{max}, and i is any current density between zero and i_{max}. By rearranging we obtain

$$\frac{P}{P_{max}} = 1 - \frac{i}{i_{max}} \tag{41}$$

Recall the relations we established in Eqs. (18), (19), and (20) based on the Nernst voltage concept to describe how the variation of a reactant partial pressure affects the voltage. Based on these relations and by replacing the P_2/P_1 terms with the P/P_{max} expression we have in Eq. (41), we establish the concentration voltage losses at the anode and cathode with hydrogen and oxygen flows as follows:

$$E_{c,\,a} = -\frac{RT}{2F} \ln\left(1 - \frac{i}{i_{max\,,\,a}}\right) \tag{42}$$

$$E_{c,\,c} = -\frac{RT}{4F} \ln\left(1 - \frac{i}{i_{max\,,\,c}}\right) \tag{43}$$

Notice the addition of the negative sign so that the outcome is a positive voltage loss value. Even though Eqs. (42) and (43) are a fair fit, they lack the gradual smoothness of actual experimental results. This is because these two equations do not take into account the effect of water and non-reacting inert gases (especially nitrogen) accumulation which leads to non-uniform current density distribution over the electrode surface area. Hence, we usually use an empirical constant (B) in Eqs. (42) and (43) to give us more accurate results. Accordingly

$$E_{c,\,a} = -B_a \ln\left(1 - \frac{i}{i_{max\,,\,a}}\right) \tag{44}$$

$$E_{c,\,c} = -B_c \ln\left(1 - \frac{i}{i_{max\,,\,c}}\right) \tag{45}$$

It is worth noting that as seen from Fig. 24, the constant difference between the thermoneutral voltage and the reversible cell voltage is due to the $T\Delta S_f$ term previously discussed in Eq. (8). This constant difference represents the minimum amount of fuel input energy that must be converted into thermal energy under ideal fuel cell conditions. This is analogous to the Carnot efficiency concept in heat engines that represents the minimum amount of input energy that needs to be converted into thermal energy between a source and a reservoir at known temperatures. The difference between the thermoneutral voltage and the actual cell voltage, as depicted in Fig. 24, represents the actual amount of heat generation within the fuel cell. When this difference is multiplied by the current density, we get what is known as the heat generation density rate curve.

The polarization curve and equation represent a zero-dimensional steady-state model for a hydrogen fuel cell under the assumption that only a single gaseous phase is present. This is one of the simplest and most common tools for the evaluation of fuel cell performance. Nevertheless, more involved multi-dimensional and multi-phase models exist where numerical iterations and software packages are used. Based on the discussions in the previous section, we will generate the polarization curve of a typical hydrogen-air PEMFC and breakdown the curve into its crossover, activation, ohmic, and concentration loss curves. We will also generate the power density curve and the density rate of heat generation curve for the same fuel cell.

If we use the expressions found in Eqs. (18), (37), (38), (39), (44), and (45) for the variables in Eq. (31), the result is the following polarization equation:

$$\begin{aligned} E = {} & \left[E^0_{rev} + \frac{RT}{nF} \ln\left(\frac{P_{H_2} P^{0.5}_{O_2}}{P_{H_2O}}\right)\right] - \left[A_a \ln\left(\frac{i_{loss}+i}{i_{0,\,a}}\right)\right] - \left[A_c \ln\left(\frac{i_{loss}+i}{i_{0,\,c}}\right)\right] \\ & - [i(R_{ele}+R_{ion}+R_{CR})] - \left[-B_a \ln\left(1 - \frac{i}{i_{max\,,\,a}}\right)\right] \\ & - \left[-B_c \ln\left(1 - \frac{i}{i_{max\,,\,c}}\right)\right] \end{aligned} \tag{46}$$

The parameters in this equation are listed in Table 15 for a typical hydrogen-air PEMFC. The values for A_a and A_c were calculated using Eq. (34) and the values in Table 15. It is important to realize that all the voltage loss terms within the square brackets in this equation are positive. Fig. 25 shows the polarization curve of the aforementioned PEMFC with voltage losses breakdown. In accordance with the previous discussions, it is clear that the activation losses dominate at low current densities with crossover losses responsible for the losses at zero current density. The ohmic losses linearly increase with increased current densities and dominate the intermediate range with the activation losses. While the concentration losses are very low until we reach the high current densities region where they dominate and are responsible for bringing the cell voltage to zero as a result of the current density reaching the maximum current density. Fig. 26 shows three out of four of the most important fuel cell performance evaluation curves (the fourth being the efficiency curve). The figure shows the opposed relation between the polarization and power density curves on the one hand and the density rate of heat generation curve on the other. The input fuel energy that is not being converted into useful electric energy is wasted as internal stack thermal energy. The power density curve shows a wide optimum range of current densities where power density is at its near-peak. This is an important observation for the stack designer and user.

The equations of the fuel cell zero-dimensional polarization model presented so far assume static variables (such as reactant flow rates); while in practice many of the variables are in flux and change with time. Hence, for practical fuel cell design, control, stability analysis, evaluation, and optimization; dynamic modeling is required. This could be realized by dividing the terms in Eq. (31) into two main components. The first being the steady components (E_{st}) and the second being the transient components (E_{tr}). The steady components include the reversible voltage and the ohmic voltage losses since they are independent of transient terms. The transient components include the more involved activation and

Table 15
Parameter values for the polarization, power, and heat generation curves.

Parameter	Value	Unit	Parameter description
ΔH_f	285,250	J mol^{-1}	Enthalpy of formation
E^0_{rev}	1.18	V	Reversible Nernst voltage at standard conditions
R	8.3145	J mol^{-1} K^{-1}	Gas constant
T	353	K	Operation temperature
n	2	–	Number of electrons involved
F	96,485	C mol^{-1}	Faraday's constant
P_{H_2}	100	kPa	Hydrogen partial pressure
P_{O_2}	21	kPa	Oxygen partial pressure
P_{H_2O}	45	kPa	Water partial pressure
α_a	0.5	–	Anode charge transfer coefficient
α_c	0.3	–	Cathode charge transfer coefficient
A_a	0.03042	V	Anode activation constant
A_c	0.05070	V	Cathode activation constant
$i_{0,a}$	0.15	A cm^{-2}	Anode exchange current density
$i_{0,c}$	1.5×10^{-4}	A cm^{-2}	Cathode exchange current density
i_{loss}	0.008	A cm^{-2}	Lost internal current density
R_{ele}	0.0	Ω cm^2	Area-specific electronic resistance
R_{ion}	0.10	Ω cm^2	Area-specific ionic resistance
R_{CR}	0.030	Ω cm^2	Area-specific contact resistance
B_a	0.045	V	Anode empirical constant
B_c	0.045	V	Cathode empirical constant
$i_{max,a}$	15	A cm^{-2}	Anode maximum current density
$i_{max,c}$	2.5	A cm^{-2}	Cathode maximum current density

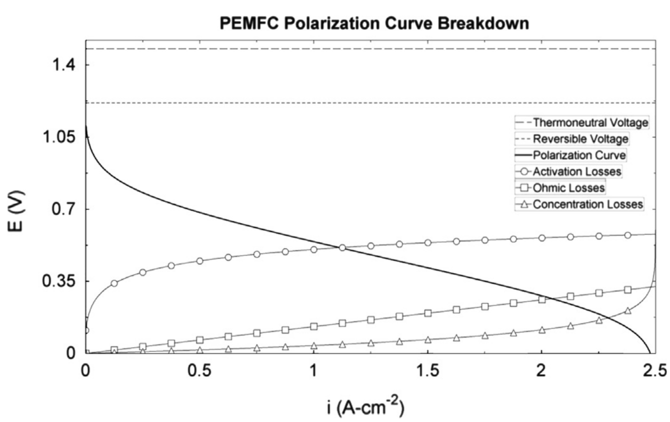


Fig. 25. PEMFC polarization curve breakdown.

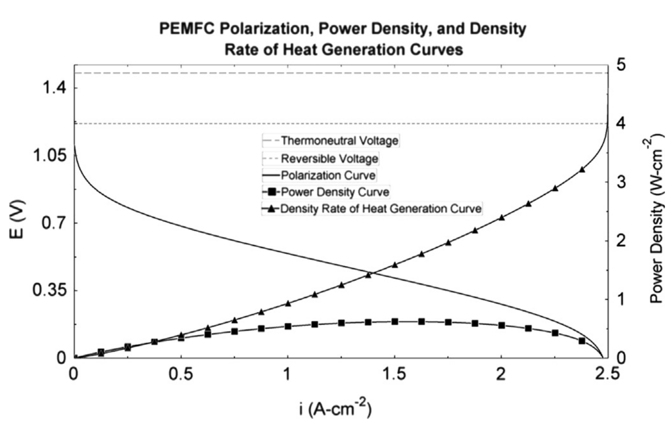


Fig. 26. PEMFC polarization, power density, and density rate of heat generation curves.

concentration voltage losses since they depend on transient terms. Accordingly:

$$E = [E_{st}] - [E_{tr}] = [E_{rev} - E_o] - [E_{a,a} + E_{a,c} + E_{c,a} + E_{c,c}] \tag{47}$$

Finding expressions for the steady and transient components in Eq. (47) could be achieved using different models available in the literature such as the fuel cell unified mathematical model described in Ref. [115].

7.5. Fuel cell system efficiency

The overall fuel cell system efficiency consists of a series of efficiencies. First of which is the reversible efficiency that was discussed in Section 7.1 and is given by Eq. (10). The second is the voltage efficiency that was discussed in Section 7.2 and is given by Eq. (16). Additionally, the fuel utilization efficiency (u_{fuel}) is the fraction of the fuel consumed within a fuel cell, the power conditioning efficiency (η_{pc}) is the efficiency of the device used to condition the output power, the onboard reformer efficiency (u_{ref}) is the fraction of the raw fuel transformed into fuel cell usable fuel, and the parasitic power efficiency takes into account the amount of fuel cell power used to operate the BoP subsystems, which is given by the following semi-empirical equation:

$$\eta_P = 1 - a - \frac{b}{Ei} \tag{48}$$

where a and b are empirical constants. When all the previously-mentioned efficiencies are combined, we get the overall fuel cell system efficiency as follows after simplification:

$$\eta_{tot} = \frac{nFE}{\Delta H_f}(u_{fuel} u_{ref} \eta_{pc})\left(1 - a - \frac{b}{Ei}\right) \tag{49}$$

By substituting the cell actual voltage in Eq. (46), using the hydrogen/air PEMFC from the previous section, into Eq. (49), we generate the total system efficiency curve in Fig. 27. Table 16 lists the parameters used in Eq. (49). We observe from the figure that for the used parameter values, the efficiency is highest around 0.5 current density. The efficiency is also very low at near-zero current densities and linearly decreases between 0.5 and 2 current densities then exponentially drops between 2 and 2.5 current densities. This implies that it is possible to optimize the design of a fuel cell by creating optimum ranges for the design parameters so as to remain within the optimum efficiency range.

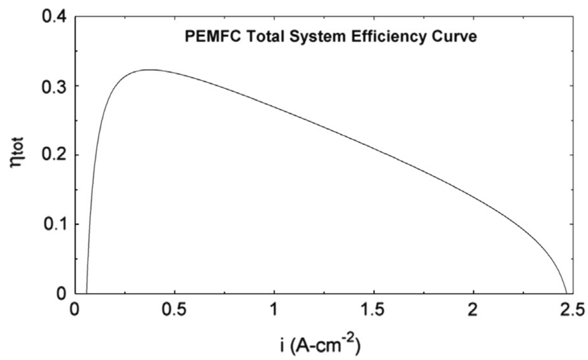


Fig. 27. PEMFC total system efficiency curve.

Table 16
Parameter values for the total system efficiency curve.

Parameter	Value	Unit
u_{fuel}	0.9	–
u_{ref}	1	–
η_{pc}	0.95	–
a	0.0499	W m^{-1}
b	0.05	–

8. Fuel cell systems evaluation factors

The evaluation and comparison of different fuel cell stacks for a certain given application is dependent on several factors. Many of these factors are case-dependent; however, it is possible to group them into the following:

- *Physical factors* include total stack size and weight, cell active area, number of cells, number of stacks, and total BoP subsystems size and weight. These are important factors when the size and/or weight of a fuel cell system are design constraints that need to be met. This is most commonly experienced for transportation and portable applications when the weight and/or size of the fuel cell system are critical constrains, as we witnessed in Section 4.
- *Performance factors* include the polarization, power density, and system efficiency curves. As evident from the previous section, it is possible to optimize the stack design by restricting the design parameters to ranges that fall into the peak power density and/or system efficiency regions. Additionally, the power density curve provides an indication of the flexibility of the output power the stack can produce. While the polarization curve, in combination with the power density curve, is usually used to determine optimum operation points in terms of voltage, current, and power.
- *Running costs* are a function of stack fuel consumption, system parasitic loads, thermal management system requirements, and efficiency of the power conditioning equipment; in addition to other case-dependent factors.
- *Durability* is also a critical factor in choosing a fuel cell stack for a certain application. This is most manifest for stationary power generation applications where the fuel cell system is expected to function for a reasonable amount of time with minimum maintenance requirements, as previously discussed in Section 4.

9. Prospects and concluding remarks

This study is a brief summary of the state of up-to-date fuel cell technologies, with a stress on the underlying but key link between application possibilities, features and characteristics, and principals of operation. An overlook over the history of fuel cells technology, competing power generation technologies, and fuel cell types have been provided. The characterizing advantages and disadvantages of fuel cells have been briefly described leading to a review of the most recent fuel cell pilot deployment and demonstration initiatives along with market status and prospects in the portable, stationary, and transportation sectors. After that, current progress and future targets for the fuel cell community have been identified in order to accelerate the market penetration rate of fuel cells. Finally, the manuscript covered the design levels, thermodynamic and electrochemical fundamentals, and system evaluation factors to offer the reader an insight into the design and operation details of fuel cell systems. Throughout the text, the authors explored global paths to the future with the aim of making fuel cells an economically-competitive player in the energy market.

A parallel approach is recommended in order to penetrate the market with a focus on DMFCs in the consumer electronics market, PEMFCs in the personal passenger vehicles market, and high-temperature fuel cells for the distributed CHP and trigeneration market. Nevertheless, the economic feasibility and reliability of fuel cells as alternatives to conventional power generation solutions are compromised by their high cost and low durability. And despite several successful pilot projects, pre-commercial demonstration initiatives, and niche market penetrations in the US, Japan, and EU; research, development, and deployment efforts should mainly target resolving the cost and durability issues before fuel cells can achieve a reasonable penetration rate into the portable, stationary, and transportation markets. Based on the discussions and findings of this study, reducing the high cost of fuel cells could be accomplished by reducing PGM loading; developing MEA fabrication processes suitable for mass production; developing durable and economic bipolar plate materials; developing economic BoP components; and simplifying fuel processing and reformation units. At the same time, increasing the durability of fuel cells in order to stand as reliable alternatives to current power generation technologies could be accomplished by improving the MEA′s contamination tolerance; developing MEA material capable of handling wide ranges of operation conditions and load dynamics; fundamentally understanding and comprehensively modeling water transport phenomena so as to develop advanced materials and optimized water management techniques; developing sealing, bipolar plate, and MEA materials and designs customized for high temperature operation; and developing mitigation strategies to handle the corrosion of platinum and its carbon support. Other issues in need of dire attention include dynamic transient operation models validated with experimental data, auxiliary components specifically optimized for fuel cell integration, standardized testing and characterizing techniques, and stack-level optimization and testing. At the end, the resolution of the cost and durability issues is likely to be directly reflected as an accelerated institution of the hydrogen infrastructure and a more accepting public, political, and industrial reception.

Indeed, fuel cells offer the highly-desirable combination of high efficiency and environmentally-benign operation that most other energy conversion devices lack; nonetheless, the development and commercialization of fuel cells have been a long and irresolute process. This is highly due to the fact that the emergence of heat engines, batteries, and similar devices has often overshadowed fuel cells for the simple fact that we have often been engrossed by the cost, efficiency, and reliability of energy generation and conversion technologies at the expense of the environmental aspect. However, as a result of the growing environmental concerns that world leaders are finally paying attention to, a revived interest in hydrogen and fuel cell technologies started during the 1990s. And as a result, more technological advances and successful commercial endeavors took place during the past two decades

compared to the period between 1839, when Grove and Schönbein demonstrated their fuel cell concepts, and the 1990s. This only calls for more attention from the academic community and more support from the public and private sectors to solve the current technological challenges facing hydrogen systems in general and fuel cells in particular in order to soon realize the full potential and benefits of a hydrogen economy.

References

[1] Polymer electrolyte membrane fuel cells. Helsinki University of Technology. 〈http://tfy.tkk.fi/aes/AES/projects/renew/fuelcell/pem_index.html〉.
[2] Space applications of hydrogen and fuel cells. National Aeronautics and Space Administration. 〈http://www.nasa.gov/topics/technology/hydrogen/hydrogen_2009.html〉.
[3] von Spakovsky MR, Olsommer B. Fuel cell systems and system modeling and analysis perspectives for fuel cell development. Energy Convers Manage 2002;43:1249–57.
[4] Gray EM, Webb CJ, Andrews J, Shabani B, Tsai PJ, Chan SLI. Hydrogen storage for off-grid power supply. Int J Hydrog Energy 2011;36:654–63.
[5] Srinivasan S. Fuel cells: from fundamentals to applications. New York: Springer; 2006.
[6] Hydrogen fuel cell engines and related technologies course manual. US Department of Energy. 〈http://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/fcm04r0.pdf〉.
[7] Sheffield JW, Sheffield Ç, editors. Assessment of hydrogen energy for sustainable development. Netherlands: Springer; 2007.
[8] Gaines L.L., Elgowainy A., Wang M.Q., Full fuel-cycle comparison of forklift propulsion systems. Argonne National Laboratory. ANL/ESD/08-3; 2008.
[9] The Department of Energy hydrogen and fuel cells program plan: an integrated strategic plan for the research, development, and demonstration of hydrogen and fuel cell technologies. US Department of Energy; 2011.
[10] El-Sharkh MY, Rahman A, Alam MS, Byrne PC, Sakla AA, Thomas T. A dynamic model for a stand-alone PEM fuel cell power plant for residential applications. J Power Sour 2004;138:199–204.
[11] Zhu Y, Tomsovic K. Development of models for analyzing the load—following performance of microturbines and fuel cells. Electr Power Syst Res 2002;62:1–11.
[12] Matheny MS, Erickson PA, Niezrecki C, Roan VP. Interior and exterior noise emitted by a fuel cell transit bus. J Sound Vib 2002;251:937–43.
[13] Karlström M. Local environmental benefits of fuel cell buses—a case study. J Clean Prod 2005;13:679–85.
[14] Grimes CA, Varghese OK, S. Ranjan. Light, water, hydrogen: the solar generation of hydrogen by water photoelectrolysis. New York: Springer; 2008.
[15] Jiao K, Li X. Water transport in polymer electrolyte membrane fuel cells. Prog Energy Combust Sci 2011;37:221–91.
[16] Ous T, Arcoumanis C. Degradation aspects of water formation and transport in proton exchange membrane fuel cell: a review. J Power Sour 2013;240:558–82.
[17] Tsushima S, Hirai S. In situ diagnostics for water transport in proton exchange membrane fuel cells. Prog Energy Combust Sci 2011;37:204–20.
[18] Varkaraki E, Lymberopoulos N, Zachariou A. Hydrogen based emergency back-up system for telecommunication applications. J Power Sources 2003;118:14–22.
[19] Elgowainy A, Gaines L, Wang M. Fuel-cycle analysis of early market applications of fuel cells: forklift propulsion systems and distributed power generation. Int J Hydrog Energy 2009;34:3557–70.
[20] Renquist JV, Dickman B, Bradley TH. Economic comparison of fuel cell powered forklifts to battery powered forklifts. Int J Hydrog Energy 2012;37:12054–9.
[21] Airport Cooperative Research Program, CDM Federal Programs Corporation, KB Environmental Sciences, Ricondo & Associates. Airport ground support equipment (GSE): emission reduction strategies, inventory, and tutorial. Transportation Research Board of the National Academies. Report 78; 2012.
[22] Tollefson J. US Congress revives hydrogen vehicle research. Nature 2009;460:442–3.
[23] Carter D, Ryan M, Wing J. The fuel cell industry review 2012. Fuel Cell Today 2012.
[24] Cowey K, Green KJ, Mepsted GO, Reeve R. Portable and military fuel cells. Curr Opin Solid State Mater Sci 2004;8:367–71.
[25] Patil AS, Dubois TG, Sifer N, Bostic E, Gardner K, Quah M, et al. Portable fuel cell systems for America's army: technology transition to the field. J Power Sources 2004;136:220–5.
[26] Horizon Fuel Cell Technologies. 〈http://www.horizonfuelcell.com〉.
[27] Heliocentris. 〈http://www.heliocentris.com〉.
[28] Wang Y, Chen KS, Mishler J, Cho SC, Adroher XC. A review of polymer electrolyte membrane fuel cells: technology, applications, and needs on fundamental research. Appl Energy 2011;88:981–1007.
[29] Breakthrough Technologies Institute. 2011 Fuel cell technologies market report. US Department of Energy. DOE/EE-0755; 2012.
[30] Liming H. Financing rural renewable energy: a comparison between China and India. Renew Sustain Energy Rev 2009;13:1096–103.
[31] Abdullah MO, Yung VC, Anyi M, Othman AK, Ab. Hamid KB, Tarawe J. Review and comparison study of hybrid diesel/solar/hydro/fuel cell energy schemes for a rural ICT Telecenter. Energy 2010;35:639–46.
[32] Bauen A, Hart D, Chase A. Fuel cells for distributed generation in developing countries—an analysis. Int J Hydrog Energy 2003;28:695–701.
[33] Contreras A, Posso F, Guervos E. Modelling and simulation of the utilization of a PEM fuel cell in the rural sector of Venezuela. Appl Energy 2010;87:1376–85.
[34] Munuswamy S, Nakamura K, Katta A. Comparing the cost of electricity sourced from a fuel cell-based renewable energy system and the national grid to electrify a rural health centre in India: a case study. Renew Energy 2011;36:2978–83.
[35] Santarelli M. Design and analysis of stand-alone hydrogen energy systems with different renewable sources. Int J Hydrog Energy 2004;29:1571–86.
[36] Khan MJ, Iqbal MT. Pre-feasibility study of stand-alone hybrid energy systems for applications in Newfoundland. Renew Energy 2005;30:835–54.
[37] Wallmark C, Alvfors P. Technical design and economic evaluation of a stand-alone PEFC system for buildings in Sweden. J Power Sources 2003;118:358–66.
[38] Agbossou K, Chahine R, Hamelin J, Laurencelle F, Anouar A, St-Arnaud JM, et al. Renewable energy systems based on hydrogen for remote applications. J Power Sources 2001;96:168–72.
[39] Shabani B, Andrews J. An experimental investigation of a PEM fuel cell to supply both heat and power in a solar-hydrogen RAPS system. Int J Hydrog Energy 2011;36:5442–52.
[40] Perrin M, Lemaire-Potteau E. Applications: stationary: remote area power supply: batteries and fuel cells. In: Garche J, editor. Encyclopedia of electrochemical power sources. Amsterdam: Elsevier; 2009.
[41] Zoulias EI, Lymberopoulos N. Techno-economic analysis of the integration of hydrogen energy technologies in renewable energy-based stand-alone power systems. Renew Energy 2007;32:680–96.
[42] Briguglio N, Ferraro M, Brunaccini G, Antonucci V. Evaluation of a low temperature fuel cell system for residential CHP. Int J Hydrog Energy 2011;36:8023–9.
[43] Gigliucci G, Petruzzi L, Cerelli E, Garzisi A, La Mendola A. Demonstration of a residential CHP system based on PEM fuel cells. J Power Sources 2004;131:62–8.
[44] Kazempoor P, Dorer V, Weber A. Modelling and evaluation of building integrated SOFC systems. Int J Hydrog Energy 2011;36:13241–9.
[45] Burer M, Tanaka K, Favrat D, Yamada K. Multi-criteria optimization of a district cogeneration plant integrating a solid oxide fuel cell–gas turbine combined cycle, heat pumps and chillers. Energy 2003;28:497–518.
[46] Margalef P, Samuelsen S. Integration of a molten carbonate fuel cell with a direct exhaust absorption chiller. J Power Sources 2010;195:5674–85.
[47] Chan CW, Ling-Chin J, Roskilly AP. A review of chemical heat pumps, thermodynamic cycles and thermal energy storage technologies for low grade heat utilization. Appl Therm Eng 2013;50:1257–73.
[48] Bendaikha W, Larbi S, Bouziane M. Feasibility study of hybrid fuel cell and geothermal heat pump used for air conditioning in Algeria. Int J Hydrog Energy 2011;36:4253–61.
[49] Ma S, Wang J, Yan Z, Dai Y, Lu B. Thermodynamic analysis of a new combined cooling, heat and power system driven by solid oxide fuel cell based on ammonia–water mixture. J Power Sources 2011;196:8463–71.
[50] Wang M, Elgowainy A, Han J. Life-cycle analysis of criteria pollutant emissions from stationary fuel cell systems. US Department of Energy Hydrogen and Fuel Cells Program. AN012;2010.
[51] Alcaide F, Cabot PL, Brillas E. Fuel cells for chemicals and energy cogeneration. J Power Sources 2006;153:47–60.
[52] Tanino T, Nara Y, Tsujiguchi T, Ohshima T. Coproduction of acetic acid and electricity by application of microbial fuel cell technology to vinegar fermentation. J Biosci Bioeng 2013;116:219–23.
[53] Plunkett JW. Plunkett's automobile industry almanac 2011. Houston, TX: Plunkett Research; 2010.
[54] Wipke K, Sprik S, Kurtz J, Ramsden T. Controlled hydrogen fleet and infrastructure analysis. National Renewable Energy Laboratory. TV001; 2010.
[55] Beckhaus P, Dokupil M, Heinzel A, Souzani S, Spitta C. On-board fuel cell power supply for sailing yachts. J Power Sources 2005;145:639–43.
[56] Blake GD. Solid oxide fuel cell development for auxiliary power in heavy duty vehicle applications. Delphi Corporation Fuel Cells and Reformers Product Team. FC_44_Blake; 2008.
[57] Brodrick CJ, Lipman TE, Farshchi M, Lutsey NP, Dwyer HA, Sperling D, et al. Evaluation of fuel cell auxiliary power units for heavy-duty diesel trucks. Transp Res Part D: Transp Environ 2002;7:303–15.
[58] Agnolucci P. Prospects of fuel cell auxiliary power units in the civil markets. Int J Hydrog Energy 2007;32:4306–18.
[59] Henne RH, Friedrich KA. Applications: transportation: auxiliary power units: fuel cells. In: Garche J, editor. Encyclopedia of electrochemical power sources. Amsterdam: Elsevier; 2009.
[60] Lutsey N, Brodrick CJ, Sperling D, Dwyer HA. Markets for fuel cell auxiliary power units in vehicles: a preliminary assessment. Institute of Transportation Studies. UCD-ITS-RP-02-44; 2002.
[61] Krumpelt M. Auxiliary power units: what, why, how, when. In: Proceedings of EU/US symposium; 2001.
[62] Gaines L., Hartman C.J.B. Energy use and emissions comparison of idling reduction options for heavy-duty diesel trucks. In: Proceedings of the 88th annual meeting of the Transportation Research Board; 2009.

[63] Qi Z. Application: transportation: light traction: fuel cells. In: Garche J, editor. Encyclopedia of electrochemical power sources. Amsterdam: Elsevier; 2009.
[64] Dicks AL. PEM fuel cells: applications. In: Sayigh A, editor. Comprehensive renewable energy. Oxford: Elsevier; 2012.
[65] Colella WG. Market prospects, design features, and performance of a fuel cell-powered scooter. J Power Sources 2000;86:255–60.
[66] Lin B. Conceptual design and modeling of a fuel cell scooter for urban Asia. J Power Sources 2000;86:202–13.
[67] Hwang J, Wang D, Shih N, Lai D, Chen C. Development of fuel-cell-powered electric bicycle. J Power Sources 2004;133:223–8.
[68] Hwang J, Wang D, Shih N. Development of a lightweight fuel cell vehicle. J Power Sources 2005;141:108–15.
[69] Wang FC, Chiang Y-S. Design and control of a PEMFC powered electric wheelchair. Int J Hydrog Energy 2012;37:11299–307.
[70] Hochgraf C. Application: transportation: electric vehicles: fuel cells. In: Garche J, editor. Encyclopedia of electrochemical power sources. Amsterdam: Elsevier; 2009.
[71] First Hyundai ix35 FCEV rolls off assembly line in Korea. Fuel Cells Bulletin 2013; 2013:2.
[72] Zorpette G. Super charged [ultracapacitors]. IEEE Spectr 2005;42:32–7.
[73] Pollet BG, Staffell I, Shang JL. Current status of hybrid, battery and fuel cell electric vehicles: from electrochemistry to market prospects. Electrochim Acta 2012;84:235–49.
[74] Campanari S, Manzolini G, Garcia de la Iglesia F. Energy analysis of electric vehicles using batteries or fuel cells through well-to-wheel driving cycle simulations. J Power Sources 2009;186:464–77.
[75] Thomas CE. Fuel cell and battery electric vehicles compared. Int J Hydrog Energy 2009;34:6005–20.
[76] Nguyen T, Ward J. Well-to-wheel greenhouse gas emissions and petroleum use for mid-size light-duty vehicles. US Department of Energy. Record#1001; 2010.
[77] Ahluwalia RK, Hua TQ, Peng JK. On-board and off-board performance of hydrogen storage options for light-duty vehicles. Int J Hydrog Energy 2012;37:2891–910.
[78] Urban buses: alternative powertrains for Europe. Fuel Cells and Hydrogen Joint Undertaking; 2012.
[79] Eudy L, Chandler K, Gikakis C. Fuel cell buses in U.S. transit fleets: current status 2012. National Renewable Energy Laboratory. NREL/TP-5600-56406; 2012.
[80] Ally J, Pryor T. Life-cycle assessment of diesel, natural gas and hydrogen fuel cell bus transportation systems. J Power Sources 2007;170:401–11.
[81] Saxe M, Folkesson A, Alvfors P. Energy system analysis of the fuel cell buses operated in the project: clean urban transport for Europe. Energy 2008;33: 689–711.
[82] Canada gets first fuel cell bus for 2010 winter Olympics fleet. Fuel Cells Bulletin 2009;2009:2.
[83] Li X, Li J, Xu L, Yang F, Hua J, Ouyang M. Performance analysis of proton-exchange membrane fuel cell stacks used in Beijing urban-route buses trial project. Int J Hydrog Energy 2010;35:3841–7.
[84] Neves NP, Pinto CS. Licensing a fuel cell bus and a hydrogen fueling station in Brazil. Int J Hydrog Energy 2013;38:8215–20.
[85] Eudy L, Chandler K. Zero emission bay area (ZEBA) fuel cell bus demonstration: second results report. National Renewable Energy Laboratory. NREL/TP-5600-55367; 2012.
[86] Fuel Cell Application. Murdoch University. ⟨http://www.see.murdoch.edu.au/resources/info/Applic/Fuelcells/⟩.
[87] Vision receives $27m purchase order for 100 fuel cell Class 8 trucks. Fuel Cells Bulletin 2012; 2012:3.
[88] Guo L, Yedavalli K, Zinger D. Design and modeling of power system for a fuel cell hybrid switcher locomotive. Energy Convers Manage 2011;52: 1406–13.
[89] Miller AR, Peters J, Smith BE, Velev OA. Analysis of fuel cell hybrid locomotives. J Power Sources 2006;157:855–61.
[90] Bradley TH, Moffitt BA, Mavris D, Parekh DE. Applications: transportation: aviation: fuel cells. In: Garche J, editor. Encyclopedia of electrochemical power sources. Amsterdam: Elsevier; 2009.
[91] Kim K, Kim T, Lee K, Kwon S. Fuel cell system with sodium borohydride as hydrogen source for unmanned aerial vehicles. J Power Sources 2011;196: 9069–75.
[92] Boeing fuel cell plane in manned aviation first. Fuel Cells Bulletin 2008; 2008:1.
[93] Fuel cells power first takeoff for DLR′s Antares aircraft. Fuel Cells Bulletin 2009; 2009:3.
[94] Uno M, Shimada T, Ariyama Y, Fukuzawa N, Noguchi D, Ogawa K, et al. Development and demonstration flight of a fuel cell system for high-altitude balloons. J Power Sources 2009;193:788–96.
[95] Fuel cell project for space launch vehicles. Fuel Cells Bulletin 2002; 2002:2.
[96] Sone Y, Ueno M, Kuwajima S. Fuel cell development for space applications: fuel cell system in a closed environment. J Power Sources 2004;137:269–76.
[97] Sone Y, Ueno M, Naito H, Kuwajima S. One kilowatt-class fuel cell system for the aerospace applications in a micro-gravitational and closed environment. J Power Sources 2006;157:886–92.
[98] First yacht with certified fuel cell propulsion. Fuel Cells Bulletin 2003; 2003:4–5.
[99] First fuel cell passenger ship unveiled in Hamburg. Fuel Cells Bulletin 2008;2008:4–5.
[100] Austrian collaboration unveils hydrogen fuel cell boat. Fuel Cells Bulletin 2009; 2009:5.
[101] Alkaner S, Zhou P. A comparative study on life cycle analysis of molten carbon fuel cells and diesel engines for marine application. J Power Sources 2006;158:188–99.
[102] Leo TJ, Durango JA, Navarro E. Exergy analysis of PEM fuel cells for marine applications. Energy 2010;35:1164–71.
[103] Third fuel cell submarine handed to German navy. Fuel Cells Bulletin 2006; 2006:10.
[104] Psoma A, Sattler G. Fuel cell systems for submarines: from the first idea to serial production. J Power Sources 2002;106:381–3.
[105] FY 2012 progress report for the DOE hydrogen and fuel cells program. US Department of Energy Hydrogen and Fuel Cells Program. DOE/GO-102012-3767; 2012.
[106] Spendelow J, Papageorgopoulos D. Platinum group metal loading in PEMFC stacks. US Department of Energy. Record#11013; 2011.
[107] Clean Energy Patent Growth Index 2012 Year in Review. Heslin Rothenberg Farley & Mesiti P.C. ⟨http://cepgi.typepad.com/heslin_rothenberg_farley_/2013/03/clean-energy-patent-growth-index-2011-year-in-review.html⟩.
[108] Fuel cell technologies office: multi-year research, development, and demonstration plan. US Department of Energy; 2011.
[109] Spendelow J, Papageorgopoulos D. Fuel cell bus targets. US Department of Energy. Record#12012; 2012.
[110] Haile SM. Fuel cell materials and components. Acta Mater 2003;51: 5981–6000.
[111] Farrington L. Fuel for thought on cars of the future. Sci Comput World 2003.
[112] Mehta V, Cooper JS. Review and analysis of PEM fuel cell design and manufacturing. J Power Sources 2003;114:32–53.
[113] Ramos-Paja CA, Romero A, Giral R, Calvente J, Martinez-Salamero L. Mathematical analysis of hybrid topologies efficiency for PEM fuel cell power systems design. Int J Electr Power Energy Syst 2010;32:1049–61.
[114] Barbir F. PEM fuel cells: theory and practice. New York: Academic Press; 2005.
[115] Xue XD, Cheng KWE, Sutanto D. Unified mathematical modelling of steady-state and dynamic voltage–current characteristics for PEM fuel cells. Electrochim Acta 2006;52:1135–44.